

Article

Ferroelectret Ultrasonic Transducers for Pulse-Echo Water Immersion

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Featured Application: Ultrasonic transducers with a short impulse response and a wide frequency band response are desirable for ultrasonic imaging and quantitative echography where the spectral analysis of reflected pulses can reveal the inner structure of scatterers and different organs in medical imaging. Therefore, the featured application for the transducers here presented is for the resonant spectral echography technique that our group is introducing in applications for materials characterization and medical imaging for quantitative echography, with special focus on layered tissues, where this technique can reveal the presence of different layers and extract their properties; examples are the cornea, the artery wall, the skin, the pleura, etc.

Abstract: Ferroelectrets are thin and porous polymeric films with a cellular microstructure, high porosity, permanent polarization and piezoelectric response. They have been used for different applications, where one of the most interesting ones is for the fabrication of air-coupled ultrasonic transducers. More recently they have been tested as water immersion transducers, showing a promising wide bandwidth but limited sensitivity along with other technical problems. This paper investigates ultrasonic transducers for water immersion and pulse-echo operation based on ferroelectret films. Two different ferroelectret foams with different resonant frequencies, acoustic impedances and cellular structures were tried. Flat and spherically focused prototypes (radius of curvature of 22 and 35 mm) were produced and tested. Finally, different materials and methods were tried to provide a protective surface coating. Acoustic field measurements for the focused transducers confirm the possibility to efficiently focus the ultrasonic beam by the proposed fabrication method, with focal spot size of 1.86 mm at −6 dB. Results show that in spite of the reduced sensitivity (about −115 dB), some of the tried ferroelectret films provide a very wide band response (−6 dB band from 0.29 to 2.7 MHz) and short pulse duration (2–3 us) that can be of interest for different applications.

Keywords: ferroelectret films; ultrasonic transducers; pulse-echo transducers; water immersion transducers; ultrasonic medical imaging; ultrasonic NDT

1. Introduction

Ferroelectrets (FE) are polymeric foam films with elongated pores in the film plane that can be poled and present a piezoelectric response [1,2]. They have been widely researched and used. One of the most interesting uses of FE films is for air-coupled ultrasonic transducers, where flat and focused designs have been used in Nondestructive Tests NDT [3–5]. The very low impedance of this type of materials permits the construction of transducers without matching layers, though the response is

quite resonant and, hence, the bandwidth reduced, alternatively they have also been used as active matching layers [6].

Flat transducers were first tried for water immersion in [3,7] where they demonstrated a poor sensitivity but a very wide band response. Later, in [8], the use of matching layers was tried to increase both sensitivity and water resistance with limited success. In spite of the poor sensitivity, the large bandwidth together with other advantages, like the flexibility and the possibility to miniaturize the transducers, motivated further study of this application. In particular, the use of different FE materials, different protective coatings and focused designs to improve resolution.

In this work, we present the pulse-echo response in water immersion of transducers based on two different FE materials with the purpose of providing some insight into the path to improve FE material properties for water coupled ultrasonic transducers. Flat and spherically focused prototypes were fabricated and tested and the use of different thin polymeric coatings intended to protect the transducer surface without having any negative impact on either the sensitivity or the frequency bandwidth were tried. Transducer response in pulse-echo operation mode (both time domain and sensitivity in the frequency domain) was measured as well as the acoustic field distribution.

2. Materials and Methods: Transducers Design and Fabrication

The purpose of this work is to study the feasibility of using ultrasonic transducers based on FE films for pulse-echo water immersion. To this end, FE transducers were designed, fabricated and tested. Two different FE materials (HS03 and HS06) were used to make ultrasonic transducers that were then tested in pulse-echo mode in water immersion. For the FE material providing the best results, spherically focused transducers were then produced and tested. Finally, different techniques and materials were investigated with the purpose of providing further protection of the transducer radiating surface without affecting transducer performance.

2.1. Ferroelectret Materials

Two different polypropylene ferroelectret films were employed to produce and test water immersion transducers. Both materials were purchased from EMFI, their commercial names are: HS03 and HS06. The properties of these materials have been widely studied before (see, for example [9,10]). The main properties of the employed FE films are summarized in Table 1. These two materials permit determination of whether the resonant frequency of the film has any effect on the pulse-echo frequency band of the transducer when operated in water immersion and if the differences in the material impedance have any impact on the transducers' sensitivity. Furthermore, these two materials present a somewhat different microstructure; see [10], where pores in HS06 are more open giving rise to a lower material density and deformability in the thickness direction. It is of interest to determine what is the material microstructure that provides better water-coupled transducers is, as this information could be used to further engineer FE properties for this application.

Table 1. Properties of the ferroelectret FE films employed [10].

Material	Thickness (μm)	Density (kg/m^3)	$\lambda/2$ Resonant Frequency, Thickness Mode (MHz)	Impedance (MRayl)
HS03	70	530	0.638	0.046
HS06	90	370	1.120	0.065

2.2. Transducer Design and Fabrication Method

Flat and spherically focused transducers were tried. In all cases aperture was circular (15 mm diameter). Two different radii of curvature were tried for the spherically focused transducers: 22 and 35 mm. In all cases, the FE film is glued to a heavy backing block (brass) and provided with aluminum housing, ground connected for radio frequency RF shielding (see Figure 1).

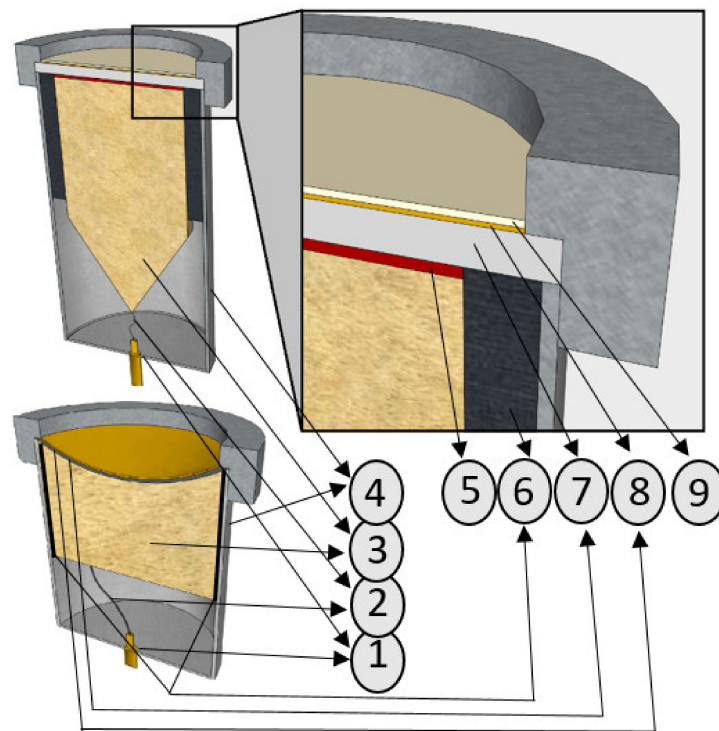


Figure 1. Transducer design for flat and spherically focused prototypes. 1: Connector, 2: wire, 3: backing block, 4: aluminum housing, 5: conductive tape, 6: insulating seal, 7: ferroelectret film, 8: Au coating, 9: Polymer coating.

The possibility of using matching layers for water-coupled FE transducers was studied in [8]. The purpose was to improve the transducer sensitivity and to provide a protection of the FE front surface and electrode. However, the main problem is that there are no available materials with the required properties to produce these matching layers. For the ferroelectret materials shown in Table 1, the required impedance for the matching layer is about 0.28 MRayl for one single matching layer and about 0.07 and 0.23 MRayl for a stack of two matching layers. Such low impedance materials can be found in porous materials like those presented in [11], however the open-cell nature of the pores of these materials makes it impossible to use them in water. Closed-cell porous materials were also tried as matching layers [12], but it is not easy to obtain close-cell porous materials with impedance below 0.3 MRayl; specially, considering that the pore size must be much smaller than the matching layer thickness. Finally, [8] revealed that the use of available materials produces a moderate improvement of the transducer sensitivity together with an unacceptable reduction in the transducers' frequency band. For this reason, the use of matching layers was discarded, however, methods to protect the transducer front surface and electrode that do not interfere with the frequency band nor reduce sensitivity have been considered in this work and are explained later.

Circles were cut out of the FE sheets, of diameter 15 mm, and glued to a brass backing block using double-sided electrically conductive tape. The front face of the FE circle is electrically connected to the cylindrical transducer housing (aluminum) that is connected to the ground electrode of the transducer. For the focused transducer, the backing block has a spherical shape. The FE film is pressed against the spherical surface, this permits the accommodation of the film to this curvature, though it also produces some wrinkles. The number and size of these wrinkles depend on the radius of the spherical backing block and the transducer aperture. The problem of adapting the flexible (but non-stretchable) ferroelectret film to non-developable surfaces has already been addressed in [13], where it was avoided by dividing the surface into small portions. When this is not possible some wrinkles may appear in the

film as is the case for spherically focused transducers. A similar effect has been observed previously in [14] for air-coupled spherically focused transducers.

The HS03 has one surface metalized with aluminum; this face is used as transducer external surface and the aluminum metallization can be used as ground electrode. The HS06 has no electroded surface. Therefore, in this case the outer surface is sputtered with gold. However, the stability of the aluminum electrode is very poor, and it can be easily removed with film manipulation or even when the transducer is operated in water. For this reason, in all cases a thin layer of gold was sputtered on the radiating surface, this electrode presents a much better resistance compared with the evaporated aluminum electrode. The Au-sputtering was performed using a Leica EM ACE200 coater with directional coating and coating time between 30 and 60 s.

Figure 2 shows a picture of some of the fabricated transducer prototypes. Wrinkles in the FE film can be seen in the focused designs, as well as the fact that there are more wrinkles and wrinkle size is larger in the transducer with the smaller radius.



Figure 2. Picture of transducer prototypes, from left to right: HS03 focused (radius of curvature: 22 mm), HS03 focused (radius of curvature: 35 mm), HS06 flat, HS03 flat.

2.3. Methods for Transducer Characterization

2.3.1. Preliminary Transducer Verification: Pulse-Echo in Air

A first verification of the proper FE film behavior in the transducer was performed by measuring the transducer response in pulse-echo in air. As it is well known, the FE film glued to a backing block and operating in air is quite a resonant device and the resonant mode is the quarter wavelength thickness resonance of the FE film. Sensitivity (*SNS*) in pulse echo is measured as:

$$SNS = 20 \log \left(\frac{|FFT(s_{Rx})|}{|FFT(s_{Tx})|} \right), \quad (1)$$

where *FFT* denotes the Fast Fourier Transform, s_{Tx} is the signal applied to transducer terminals and s_{Rx} is the electrical signal generated in the transducer when the echo is received. In order to obtain these signals a temporal square gate is applied. In the first case the gate is located at $t = 0$ s, while in the second case the gate is located at the time of arrival of the echo. We used an Olympus 4077 pulser-receiver PR in pulse-echo mode to drive the transducer with a half cycle square pulse, 400 V amplitude, 1.0 MHz center frequency, and to receive and amplify (40 dB) the received echo. Signals were digitized and stored using a Tektronix DPO oscilloscope.

The advantage of this way of verifying transducer fabrication is that it is simple and fast. Any lack of resonant response or a response more damped than expected or a significant deviation of the resonant frequency away from the expected value ($\lambda/4$ thickness resonance) can easily be interpreted as defective design that can be attributed to a damaged FE film, or electrode, or to an imperfect binding

of the FE film to the backing block. Table 1 shows the value of the $\lambda/2$ thickness resonance measured in [10] in free standing films, so the $\lambda/4$ frequency is simply $\frac{1}{2}$ of the $\lambda/2$ resonant frequency shown in Table 1.

2.3.2. Transducer Characterization: Pulse-Echo Measurements in Water Immersion

The experimental set-up for pulse-echo measurements is shown in Figure 3; transducers and a flat steel block (53 mm thick) used as reflector were immersed in a water tank. The transducer is driven by the an Olympus 5058 pulser/receiver, the received echo is received through the receiver stage of the Olympus 5058 PR, filtered, amplified (40 dB) and then sent to an oscilloscope where the signal is digitized and stored. For the focused transducers, the reflector is located at the transducer focal distance, while for the flat transducer, the separation was 40 mm (which is close to the transition between near and far field).

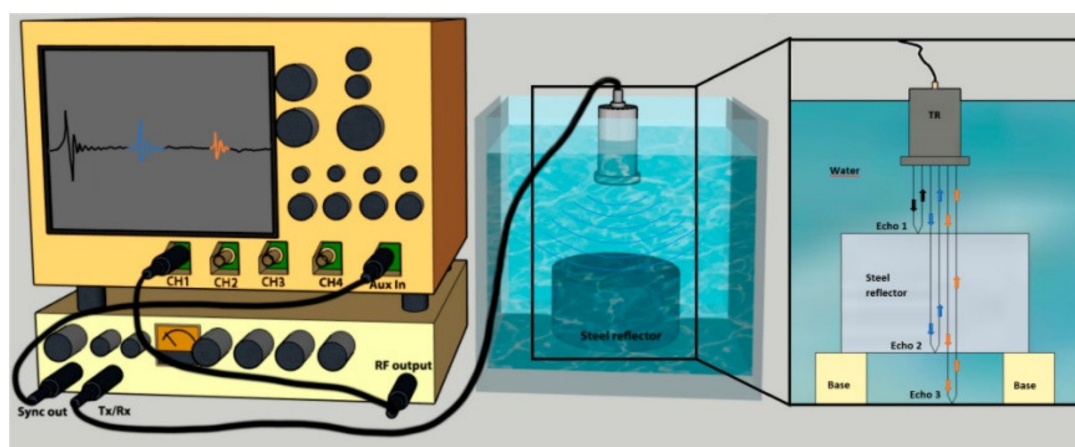


Figure 3. Experimental set-up for pulse-echo measurements.

2.3.3. Transducer Characterization: Acoustic Field Measurements in Water Immersion

An XYZ scanner DIS300 and a Difrascopie pulse-echo ultrasound equipment were used, both from DASEL SL (Madrid, Spain). For each transducer, the acoustic field was measured over a rectangular grid, using a 1 mm diameter needle hydrophone (Precision Acoustics, Dorchester, Dorset, UK) connected to the reception stage of the pulse-receiver system. The excitation, acquisition and movement were synchronized by a rotary encoder in one of the scanner axes, with a resolution of 0.1 mm.

A single negative square pulse of -400 V amplitude and 250 ns width was used for excitation, and a band-pass filter between 30 kHz and 5 MHz was applied on reception, along with averaging by 8 to improve signal to noise ratio. For each position of the measurement grid, the peak-to-peak value was registered, to build the normalized field plots. The time-of-flight between the transducer and the hydrophone was also registered, to account for measurement gap near the transducer surface. Measurement grid resolution was 1 mm for the flat transducer, 0.5 mm for the $f = 35$ mm transducer, and 0.2 mm for the $f = 22$ mm transducer. Signal processing and image reconstruction were performed in Matlab (Matworks Inc., Beltsville, MD, USA).

2.4. Methods for Radiating Surface Protection

Different techniques and materials were tried to provide an additional protection of the transducer surface while avoiding any reduction in either sensitivity or bandwidth: polymethylmethacrylate PMMA deposited by spin coating and polytetrafluoroethylene PTFE, varnish and acrylic lacquer (used for conformal coating for insulation and circuit boards environmental protection) deposited by spray coating, see Table 2.

Table 2. Coating material properties and method employed.

Material	Density (kg/m ³)	Ultrasound Velocity (m/s)	Acoustic Impedance (MRayl)	Coating Method
PMMA	1150	2700	3.11	Spin coating
PTFE	2200	1400	3.10	Spray coating
Varnish	950 **	1800 *	0.95	Spray coating
Acrylic Lacquer	800 **	1800 *	0.88	Spray coating

* Estimated.; ** According to manufacturer data.

PMMA powder was first dissolved in anisole (5%), deposited on transducer surface and then spin coated in two steps, first, 10 s at 1000 rpm and then 10 s at 2000 rpm. Continuity and uniformity of the coating were verified by observing the transducer surface under a microscope. The employed lacquer and varnish are UV fluorescent, so UV illumination was used to make the presence of the coating material clearer. All coatings were allowed to cure or dry for 24 h at room conditions. Thicknesses of the layers of coating were estimated from the frequency shift of the transducer thickness resonance, measured in pulse-echo in air, and from properties of the deposited materials (see Table 2).

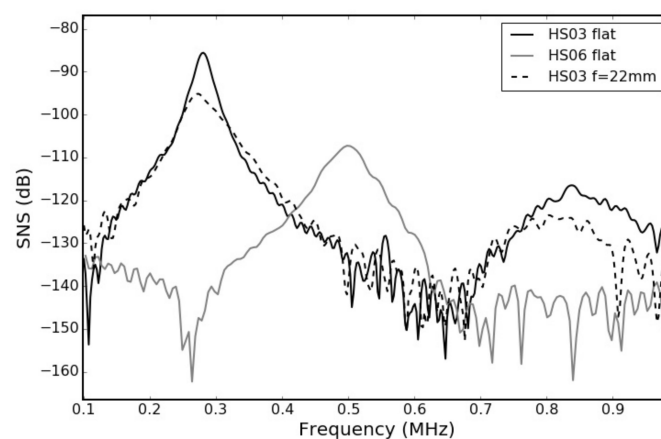
3. Results

3.1. Preliminary Verification of the FE Film Response

This preliminary verification is performed as explained in Section 2.4. This procedure was applied to uncoated flat and focused transducers to verify the proper integration of the FE layer in the transducer design and to coated flat transducers to determine the influence of the coating.

3.1.1. Basic Design: Transducers without Surface Protection.

The resonant frequency in air of the HS03 and the HS06 transducers corresponds to the $\lambda/4$ thickness resonance of the FE film. Hence, the resonant frequency is expected to be located close to 0.32 and 0.56 MHz, for HS03 and HS06, respectively (see Table 1). Measured SNS of the gold coated transducers operated in pulse-echo mode in air is shown in Figure 4.

**Figure 4.** Au-sputtered transducers in pulse-echo response, air-coupled operation.

In all cases, the resonant response is clearly observed, however, the resonance is located at a lower frequency compared with the expected $\lambda/4$ thickness resonant frequency (see Table 1). This is an expected result and is due to the effect of the layer of gold, as the gold loads the resonance and then shifts the resonant frequency towards lower values. Nonetheless, it can be confirmed that the thickness resonance is preserved and that the frequency shift is moderated. This deviation in the

resonant frequency (about 10%) is common in all Au coated transducers, this permits to estimate the thickness of the Au layer which is typically in the range 65–110 nm, for sputtering times between 30 and 60 s.

For the HS03 film the first two orders of resonances have been observed, revealing the effect of the increase in the ultrasound attenuation in the FE material with the frequency. For the HS06 film a lower sensitivity and more damped resonance is observed. This can be due to the increase in the attenuation with the frequency, or the higher impedance of this film (poorer matching to the air), or a reduced piezoelectric response compared with HS03, which could be due to a lower polarization level or to a lower piezoelectric constant that could be related to the different cellular structure of these two films, see [10].

For the HS03 focused transducer a similar resonant behavior is observed with the same resonant frequency, though it presents a somewhat lower peak SNS value that can be due to the wrinkles introduced in the FE film when it is glued to the spherical backing block. Figure 4 shows, as an example, the SNS in air of the HS03 transducer with the smaller radius of curvature.

3.1.2. Transducers with a Polymer Coating

HS03 transducers with different coatings were fabricated and the pulse-echo response in air compared before and after coating deposition. The purpose was to estimate the effect of the coating on the resonant response of the FE film: the thicker the coating, the larger the frequency shift and the lower the coating uniformity the larger the reduction in the resonance Q-factor. The measured SNS in pulse-echo mode in air, using the same equipment as in the previous section is shown in Figure 5. The frequency shift of the $\lambda/4$ thickness resonance of the transducer operated in air in pulse-echo mode is shown in Table 3.

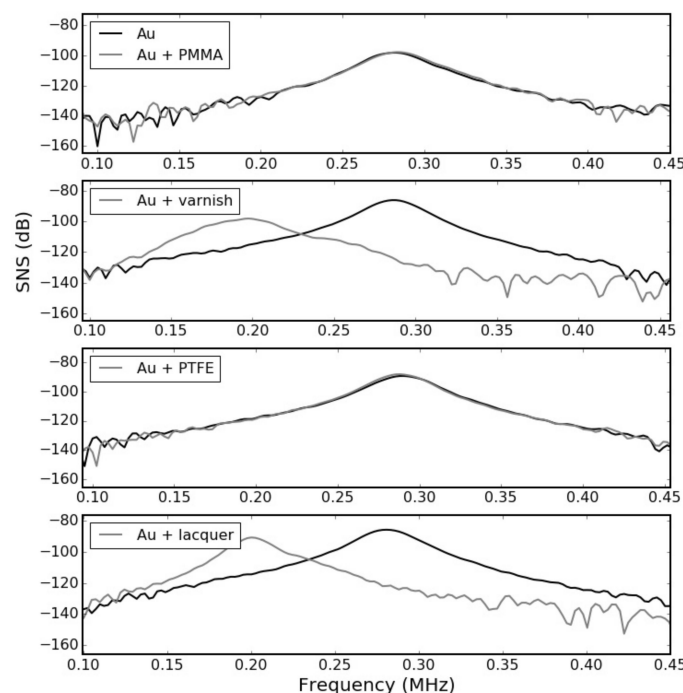


Figure 5. Sensitivity (SNS) vs. frequency for flat HS03 transducers with different coatings in pulse-echo mode in air.

Table 3. Frequency shift due to the coating and estimated coating thickness.

Coating	$\lambda/4$ Resonance (kHz)		Relative Variation (%)	Estimated Coating Thickness (μm)
	Before Coating	After Coating		
PMMA	285.6	283.2	0.85	0.3
PTFE	290.5	288.0	0.84	0.15
Varnish	280.8	200.2	28.7	25
Lacquer	285.0	200.0	29.8	26

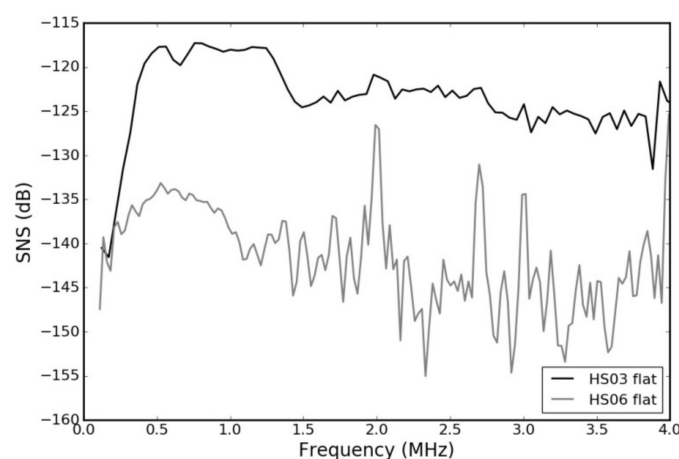
3.2. Water Immersion Response in Pulse-Echo Mode

All measurements presented in this section were performed as described in Section 2.3.2 of methods for transducer characterization.

3.2.1. Frequency Domain Response

- Response of transducers made with different FE materials

The measured SNSs in pulse-echo mode in water immersion for flat HS03 and HS06 transducers without any coating (apart from the layer of sputtered Au) are shown in Figure 6. The response of the HS03-transducers is clearly better than that of the HS06-transducer. The sensitivity of the HS03 transducer is about 15 dB higher. The bandwidth of the flat transducers made with the HS06 film is narrower, more resonant and centered at a lower frequency (about 0.6 MHz). In addition, for frequencies over 1.2 MHz the signal to noise ratio is very poor and peaks observed for HS06 between 2 and 3 MHz are due to the noise. On the contrary, the HS03 transducer presents a wider frequency band: rather flat between 0.4 and 1.3 MHz. Between 1.5 and 4.0 MHz it is also flat but 6 dB below. Beyond 4.0 MHz, the signal to noise ratio becomes very low, in part due to the lower energy output of the pulser at those frequencies. The main drawback of these transducers is the reduced peak sensitivity that is about -117 and -130 dB for HS03 and HS06, respectively.

**Figure 6.** Pulse-echo sensitivity vs. frequency.

Due to the worse performance of HS06-transducers the rest of the study (performance of focused transducers and effect of surface coating) is limited to HS03-transducers.

- Response of focused transducers.

Figure 7 shows the measured sensitivity (SNS) for the flat and the spherically focused transducers with focal distance of 22 and 35 mm. The obtained response is pretty similar, so it can be concluded

that the effect of adapting the FE film to the spherical surface of the backing block has a limited effect on the transducer performance.

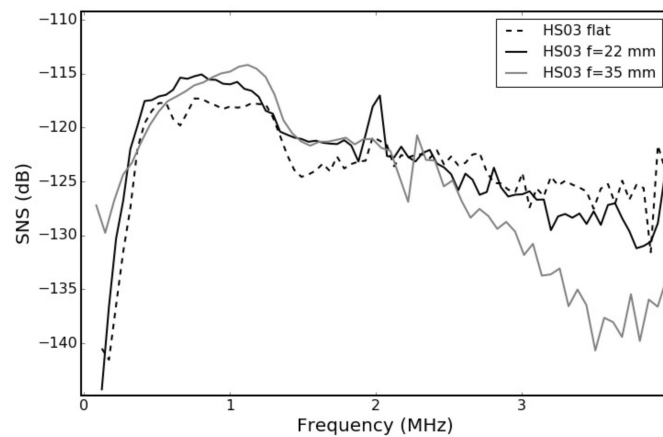


Figure 7. SNS vs. frequency for HS03 transducers in pulse-echo mode in water: flat and spherically focused (two focal distances: 22 and 35 mm).

- Response of transducers with different surface protection coatings.

Figure 8 shows the measured SNS vs. frequency for the HS03 flat transducers with different coatings. The response below 1.5 MHz is similar, but above 1.5 MHz the signal to noise ratio SNR is poorer in this case compared with the uncoated transducers.

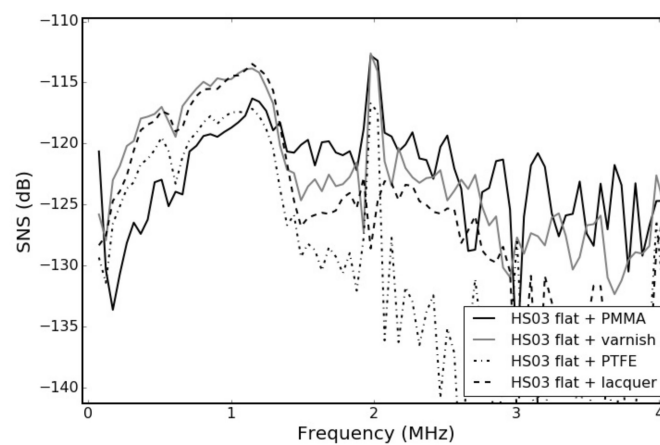


Figure 8. SNS vs. frequency for flat HS03 transducers in pulse-echo mode in water with different coatings.

3.2.2. Time Domain Response

All measurements presented in this section were performed as described in Section 2.3.2 of methods for transducer characterization.

- Flat and focused transducers.

The received echoes for the HS03 flat and focused transducers corresponding to the experimental set-up shown in Figure 3 are shown in Figure 9. For the flat transducer it is possible to see the first reflection from the water/steel surface (echo #1 in Figure 5) that appears at $\sim 57 \mu\text{s}$ (Figure 9, top), and the first reverberation in this cavity (transducer-reflector), at $\sim 115 \mu\text{s}$ (Figure 9, top). In addition, echoes from: (i) the back surface of the steel block (echo #2 in Figure 5), at $\sim 75 \mu\text{s}$ (Figure 9, top), (ii) the bottom surface of the water tank (echo #3 in Figure 5), at $\sim 87 \mu\text{s}$ (Figure 9, top), and (iii) reverberations

in those cavities can also be appreciated. For the focused transducers (focal distances of 22 and 35 mm) only the reflections from the front steel reflector surface (and reverberations in the transducer–reflector cavity) are observed as the other interfaces mentioned above are well out of focus. For the 22 mm radius of curvature transducer, the first reflection from the steel reflector front face (at $\sim 29 \mu\text{s}$) plus two reverberations in the cavity between the transducer and the reflector can be observed (at $\sim 57 \mu\text{s}$ and $\sim 85 \mu\text{s}$).

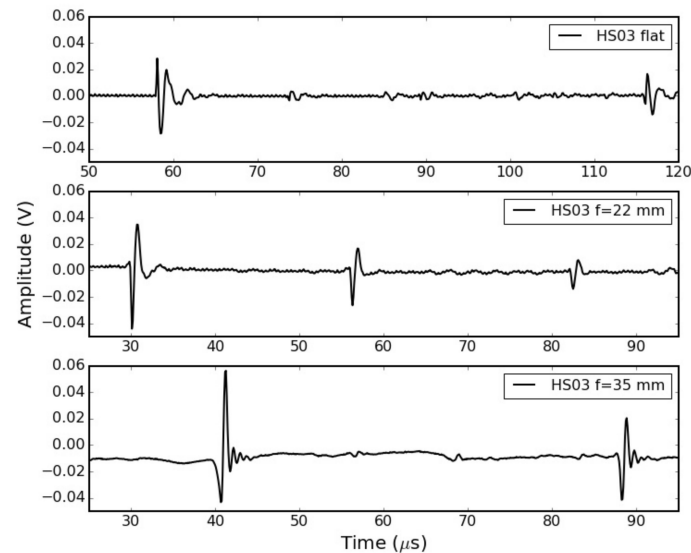


Figure 9. Response in the time domain in pulse-echo mode in water for the HS03 flat and focused transducers, radii of curvature of 22 and 35 mm.

- Transducers with coating.

The received echoes corresponding to the experimental set-up shown in Figure 5 for the HS03 flat transducers with different coatings are shown in Figure 10.

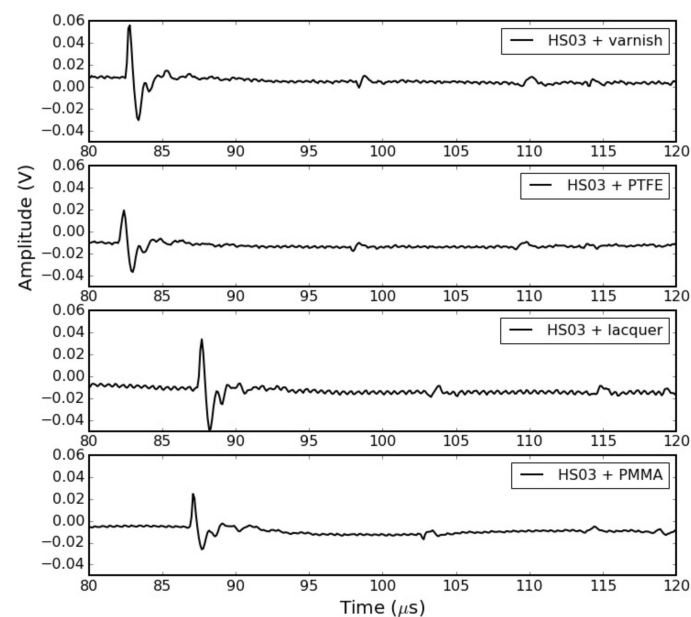


Figure 10. The response in the time domain in pulse-echo mode in water for HS03 transducers with different coatings (varnish, PTFE, lacquer and PMMA).

3.2.3. Acoustic Field

All measurements presented in this section were performed as described in Section 2.3.3.

The measured acoustic field (axial and transverse, at focal distance) distribution is shown in Figures 11–13 for HS03 transducers: flat and spherically focused with radii of curvature of 35 mm and 22 mm, respectively.

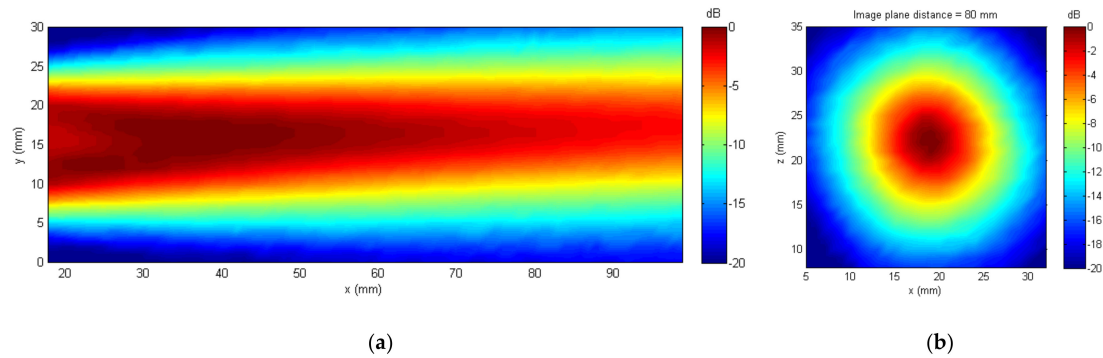


Figure 11. HS03 flat transducer acoustic field. (a) axial section, (b) transversal section.

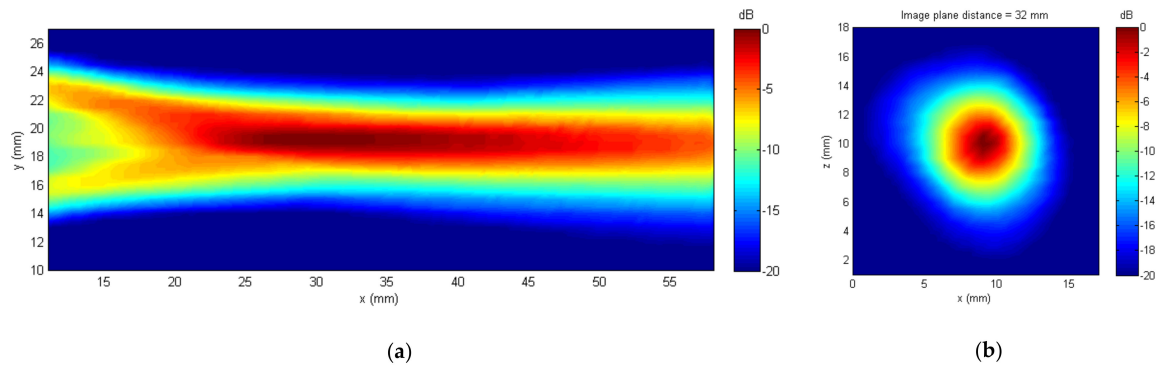


Figure 12. HS03 spherically focused transducer (radius of curvature 35 mm) acoustic field. (a) axial section, (b) transversal section.

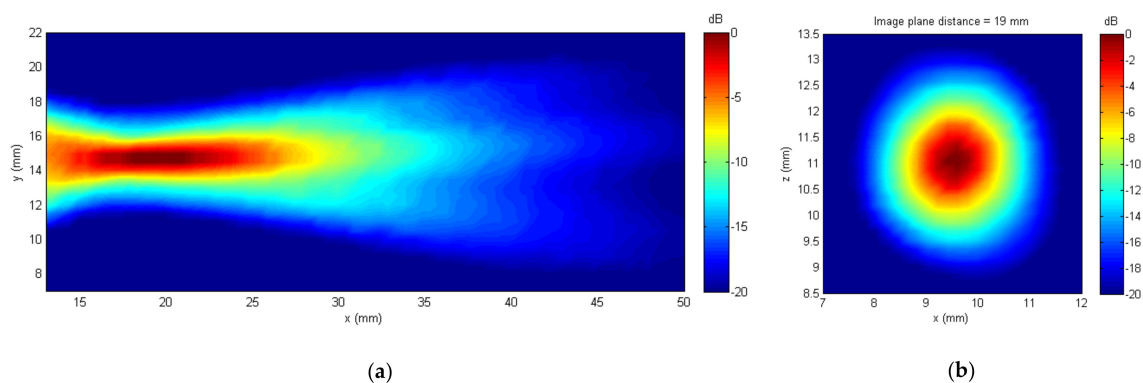


Figure 13. HS03 spherically focused transducer (radius of curvature 22 mm) acoustic field. (a) axial section, (b) transversal section.

The measured center frequency, focal distance and beam width at focus are shown in Table 4. In addition, the theoretical beam width (BW) calculated according to Equation (2) is also shown.

$$BW = 1.02 F \lambda / (D) \quad (2)$$

where F is the focal distance, λ is the wavelength and D the transducer aperture diameter.

Table 4. Focal distance and beam width at focus.

Transducer (Radius Curvature)	Measured Center Frequency	Measured Focal Distance	Beam Width at Focus	
			Theoretical	Measured
22 mm	1.30 MHz	19 mm	1.67 mm	1.8 mm
35 mm	1.20 MHz	32 mm	2.88 mm	3.7 mm

4. Discussion

The objective of this work was to test the possibility of using FE films to produce water immersion transducers for pulse-echo operation. Two different FE materials were employed: HS03 and HS06. The former has a lower resonant frequency, a more flattened pore structure (that makes the pores and the film more deformable in the thickness direction), and a lower acoustic impedance. Results with these two materials reveal that transducers produced with the HS03 film have a sensitivity about 15 dB better and a wider frequency bandwidth (Figure 6). Considering that the impedance of the HS06 film is better coupled to the water, this better response of the HS03 film could be related with either a better piezoelectric response of HS03 or a more efficient response of the cellular structure of HS03 when operated with a water load.

Water is a huge mechanical load for the FE film; hence, thickness resonances are expected to be completely damped out. As a matter of fact, no trace of the film thickness resonance is found in the pulse-echo response in water, where the film could be expected to operate in the $\lambda/2$ thickness mode (Figure 6). This huge load imposed by the water is expected to produce a very large frequency bandwidth and a very low sensitivity. Pulse duration (under spike excitation) is about 2–3 μ s long (Figures 9 and 10), while the 6 dB frequency band expands from 0.29 up to 2.7 MHz (161%), and the 12 dB band expands up to 4.5 MHz (Figures 6 and 7). The main counterpart is the reduced sensitivity. The observed peak sensitivity values for the different prototypes are in the range of -114 to -118 dB (Figures 6–8). Nonetheless, even with this low sensitivity it was possible to observe the front and back echoes of a 53 mm thick steel block (see Figures 9 and 10).

Different techniques and materials were tried to provide protection for the radiating surface. The main idea is to provide a uniform and thin coating with acoustic properties similar to the water, so that the effect of this coating on the acoustic performance could be negligible. Measured response in pulse echo mode in water immersion revealed a somewhat better sensitivity (about 5 dB) for transducers with varnish and lacquer compared with PMMA and PTFE coated transducers. This can be due to the fact that the acoustic impedance of PMMA and PTFE coatings is expected to be higher than that of the water. However, the SNR of coated transducers seems to be poorer in coated transducers (Figures 7 and 8). This has to be confirmed in further studies.

Finally, we have shown that it is possible to produce spherically focused transducers, by using a backing block with a spherical surface and gluing the FE film to it. Adapting the FE film to the curved surface produces some wrinkles in the film, however the effect on the ultrasonic response is reduced (Figures 4 and 7) and no artifacts can be observed in the acoustic fields (Figures 11–13). SNS and the signal in the time domain (Figure 9) are very similar for flat and focused transducers. The measured acoustic field of the focused transducers revealed a field distribution very close to the expected one. For the transducer with a radius of curvature of 22 mm, the measured focal distance was 19 mm and the focal spot size was 1.8 mm. In this case the calculated focal spot size was 1.67 mm, very close to the measured value. For the transducer with a radius of curvature of 35 mm, the measured focal distance was 32 mm and the focal spot size was 3.7 mm. In this case the calculated focal spot size was 2.88 mm.

5. Conclusions

This work shows the response of ferroelectric film-based transducers for pulse-echo operation in water. Two FE films were tried and the best results were obtained with the film (HS03) with the highest density and the lowest impedance. As the impedance matching is poorer for this film, the better

response must be due to a better piezoelectric response of the HS03 film. As expected, and due to the large load of the water, the thickness resonance of the film is completely damped out, giving rise to a poor sensitivity (around -115 dB) and a very wide band response with a short signal duration. It has been shown that it is also possible to produce spherically focused transducers with a similar response compared with flat ones, but with the advantage of a better spatial resolution, with a focal spot size <2 mm.

In spite of the reduced peak sensitivity, the huge bandwidth and the observed SNR values still permit to consider the use of this kind of transducers for different water immersion applications related to materials characterization, NDT and medical imaging, in applications where large bandwidth, moderate frequencies (0.5–4.0 MHz) and good axial resolution are required. In addition to the large frequency bandwidth and short signal duration, the FE transducers offer other advantages related to the flexibility of the material and the reduced size of the required backing block. Further studies are needed to determine if the transducer sensitivity can be improved. The first step can be to try techniques that have already been tested for FE air-coupled transducers. They include the use of a high voltage excitation to make the FE film work under the electrostrictive regime and the use of a bias voltage [15]. In addition, spread spectrum signals with programable excitation spectral shape can be used to compensate the 10 dB spectral losses beyond 2.0 MHz, making received signals even more broadband [16]. In addition, further studies of transmission and reception sensitivity and frequency bands could be beneficial in order to optimize transducer design.

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