EMFIT Ferroelectret Film Transducers for Non-Contact Ultrasonic Testing

Viktor BOVTUN, Institute of Physics ASCR, Prague, Czech Republic and Federal Institute for Materials Research and Testing, Berlin, Germany
Joachim DÖRING, Jürgen BARTUSCH, Uwe BECK, Anton ERHARD, Federal Institute for Materials Research and Testing, Berlin, Germany
Yuriy YAKYMENKO, NTUU "Kyiv Polytechnic Institute", Kyiv, Ukraine

Abstract. Cellular polypropylene ferroelectret films, combining strong electromechanical (EM) response with a low density and softness, are considered as a promising material for the air-coupled ultrasonic (ACUS) transducers. Our impedance spectroscopy study of the commercially available EMFIT films reveals acceptable EM properties: EM resonance above 500 kHz, very low acoustic impedance Z_A, low dielectric and mechanic losses, absence of dielectric dispersion out of EM resonance. Low coupling factor K complicates the application, but taking in to the account both important parameters, K and Z_A, EMFIT film has advantages in comparison with a PVDF film or piezoelectric composites. Influence of electrode materials (metal, thickness, deposition technology) on the EM properties was investigated. Electron beam evaporation technology was adapted to the EMFIT films to prepare samples with Au and Al electrodes without reducing or suppressing of the EM properties. Prototype transducers, based on EMFIT film, were developed. In spite of the simple construction and absence of matching layers, high sensitivity of the EMFIT transducers was proved in the ACUS experiment. Both reflected and transmitted pulses were detected through the air path length up to 50 cm. EMFIT transducers were used as a sender/receiver of the ACUS system "USPC 4000 AirTech Hillger". Amplitude and delay time scanned images of the polyethylene step wedge with holes, obtained in both pulse-echo and transmission modes, demonstrate that non-contact ultrasonic testing with EMFIT transducers is possible.

1. Introduction

A non-contact ultrasonic techniques, where air is the only coupling medium, expand the capability of ultrasonics and allow the development of simple, versatile, reliable and harmless inspection systems for industrial and medical applications, materials research and development, non-destructive testing [1-5]. The main problem of air-coupled ultrasonic (ACUS) techniques is the very high acoustic impedance (Z_A) mismatch between air and transducers, which is responsible for the high attenuation of the information carrying signal between transmitter and receiver [2,3,6]. The losses due to the impedance mismatch can be reduced by improvement of the classical piezoelectric or electret transducer design (matching layers, membranes, back plate holes, etc.) and use of the pulse-compression techniques [2,6,7]. A number of non-contact ACUS transducers (with a sensitivity typically 30 dB below the contact transducers) and complete testing systems are already commercially available [2,4,8]. However, construction and production of the available piezoceramic non-contact ACUS transducers is very complicated and, consequently, the transducers are expensive. Multiple matching layers, which should be used together with the piezoceramic active element, works properly only in the narrow frequency range and limit the bandwidth of the transducers. Therefore another approach, focusing on the search and development of new piezoelectric or electromechanically (EM) active materials with low Z_A, more adjusted to the air-coupled applications, is also of interest. Even the same level of losses, which has been already achieved in the frame of transducer design, can be considered as a success of material development approach because of the advantages of more simple construction and technology, of lower price.

A number of piezoelectric materials were developed during the last decade. Polymer and composite (ceramic-polymer) piezoelectrics are characterised by lower acoustic impedance than traditional piezoceramics [9]. But their acoustic impedance is still high and they do not provide much better adjustment to the air than ceramic piezoelectrics. The new electret materials based on smart soft polymer foams seem to be much more interesting and promising for the ACUS applications. The cellular polypropylene ferroelectret film EMFIT (Emfitech Ltd, Finland) [10-12] is an example of the smart polymer foam. Being charged, it contains many built-in electric dipoles and behaves similar to ferroelectrics [13-15]. This ferroelectret film, combining strong electromechanical response with a low density and softness, is considered as a promising material for ACUS transducers.

Here we summarise results of our impedance spectroscopy study of the commercially available EMFIT films [16,17], investigation of the influence of electrode materials (metal, thickness, deposition technology) on the electromechanical properties of EMFIT films and adaptation of the deposition technology (electron beam evaporation) to the soft EMFIT films [17] for the electrode creation without reducing or suppressing of the EM properties. ACUS transducers, based on the EMFIT films, were developed and we report the results of their test in the ACUS experiment and discuss perspectives of the cellular polypropylene ferroelectret films for the air-coupled ultrasonic applications.

2. Experimental

We studied [16,17] a few kinds of the commercially available cellular polypropylene ferroelectret EMFIT films and sensors [12,18,19]: 1) films without any electrodes and laminated layers; 2) film with a one-sided aluminium (Al) electrode evaporated directly to the film, without any laminated layers; 3) film with a one-sided Al electrode evaporated to the laminated polyester layer; 4) S-series and R-series sensors with signal, ground and shield electrodes screen-printed to the laminated polyester layers.

Because no EMFIT films with electrodes on both sides and without extra laminated polyester layer were commercially available, we deposited electrodes to the EMFIT films using our own facilities. Taking into account the extreme softness and susceptibility of the ferroelectret film, one can suppose a significant influence of the electrode mass on the electromechanical properties. This motivated us to investigate the influence of the electrode material and thickness. The working temperature range of the polypropylene EMFIT films is limited to 50°C [12]. This strongly requires optimisation of the deposition technology to avoid overheating and loss of electromechanical properties of the film. The sputtering is not the technique of our choice because an interaction with plasma will easily result in the film temperature beyond 100°C. Therefore, electron beam evaporation is the only techniques that can be applied. As electrode materials, aluminium and gold layers with thickness of 100 nm, 200 nm and 300 nm have been evaluated. Because plasma pre-cleaning would increase the EMFIT film temperature, the deposition was carried out on the EMFIT films as delivered. To improve adhesion of the aluminium and gold layers, an additional chromium sub-layer with a thickness of about 10 nm was applied for some samples. As a result, the film temperature remained below 50 °C during the deposition. Nevertheless, sufficient adhesion of the aluminium and gold layers on the EMFIT films was achieved.

The films with electrodes were embedded in a measuring cell which can be considered as a prototype EMFIT sensor (named sensor below). All samples described above: commercially available EMFIT films and sensors, films with evaporated electrodes and films embedded in sensor were characterised by impedance spectroscopy [16,17].

To prove the sensitivity, sensors with embedded EMFIT film were used as transducers in the air-coupled ultrasonic experiment performed by means of Panametrics Pulser / Receiver 5800 and Yokogawa Digital Oscilloscope DL 7100. Both pulse reflection from the metal plate (using one EMFIT transducer in the pulse-echo mode) and pulse transmission between two EMFIT transducers were measured. The air path length between the transmitter and receiver was varied from 1 cm to 50 cm. EMFIT transducers were used as a sender/receiver of the ACUS system “USPC 4000 AirTech Hillger", to obtain amplitude and delay time scanned images of the inhomogeneous relief object (polyethylene step wedge with holes) in both pulse-echo and transmission modes (see details in [20]).

3. Impedance Spectra of the EMFIT Films and Sensors

Impedance spectroscopy of the EMFIT films reveals features unusual for the typical piezoelectric materials, which reflect an extreme softness of the ferroelectret film along 33-direction, perpendicular to the surface, and anisotropy due to the layered structure and the lens-like shape of the voids [11,13,14,17]. The in-plane electromechanical properties are suppressed. Generally, electromechanical resonance does not dominate in the impedance / admittance response of the ferroelectret film, not even near the resonance frequency. The thickness resonance anomalies (see Figures 1 and 2) are weak comparatively to that of ferroelectric polymers or piezoceramics [9] and are superimposed on the dominating pedestal formed by the impedance (or respectively admittance) of low-loss capacitor.

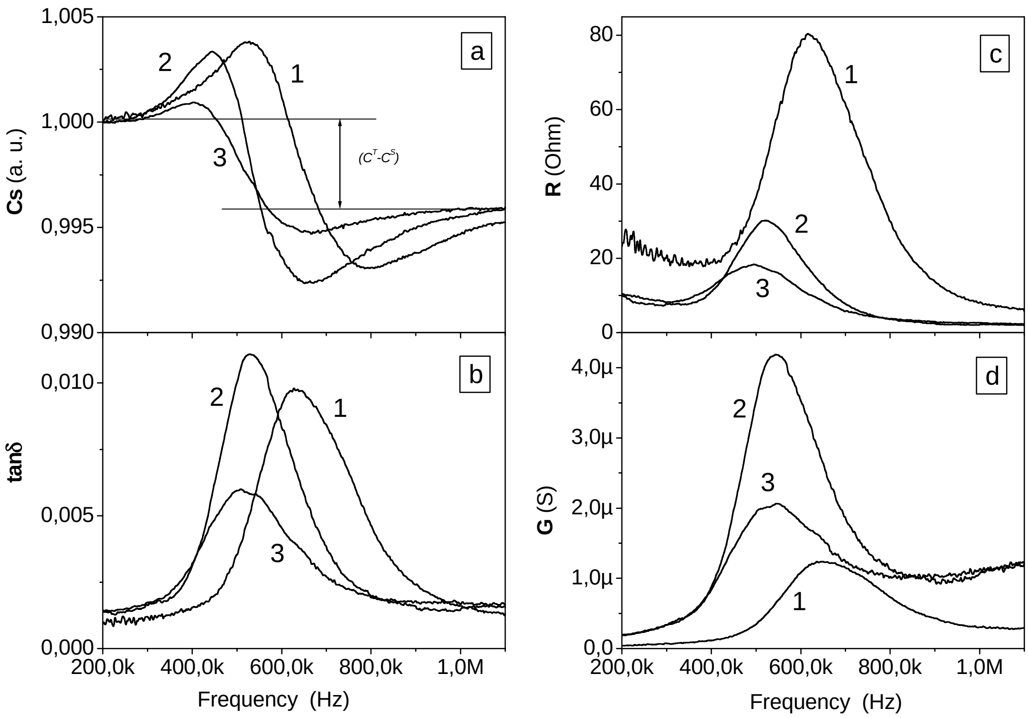

Figure 1. Electromechanical resonance of EMFIT films with evaporated Cr/Au electrodes (10 nm Cr, 200 nm Au). Frequency dependences of the normalised serial capacitance C_s (**a**), dielectric losses tanδ (**b**), real part of impedance R (**c**) and real part of admittance G (**d**) of the films without electrodes (**1**), with electrodes (**2**) and with electrodes embedded in sensor (**3**).

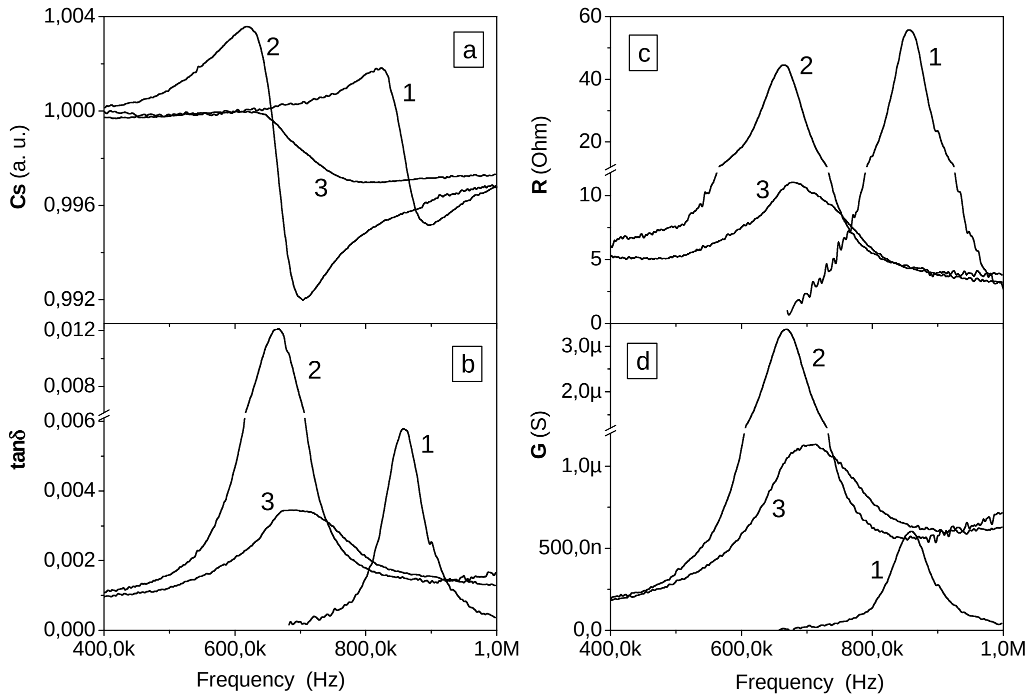

Figure 2. Electromechanical resonance of EMFIT films with evaporated Al electrodes (100 nm). Frequency dependences of the normalised serial capacitance C_s (**a**), dielectric losses tanδ (**b**), real part of impedance R (**c**) and real part of admittance G (**d**) of the films without electrodes (**1**), with electrodes (**2)** and with electrodes embedded in sensor (**3**).

Therefore ferroelectret sensor is to a great extent a low-loss capacitor, which should be taken into account at the equivalent scheme analysis or modelling.

Small difference between the parallel and serial resonance frequencies (see Figures 1c, 1d and 2c, 2d) evidences the low electromechanical coupling. Coupling factor, estimated from the difference between the mechanically free (C^T) and mechanically clamped (C^S) capacitance (Figure 1a) according to the equation $C^T = C^S(1+K^2)$, proves it: $K \approx 0.06$ for all measured EMFIT films without electrodes or with thin enough electrodes.

Dielectric losses of the EMFIT films are very low, in spite of the large electric charge injected by corona charging and numerous built-in electric dipoles. No significant dielectric dispersion was observed in frequency range from 10 kHz to 40 MHz, except anomalies related to the electromechanical resonance. Dielectric permittivity of the EMFIT films is very low ($\varepsilon^T = 1.1 \div 1.2$) reflecting a great volume fraction of the air-filled voids. Absence of dielectric dispersion and low losses evidence no influence of the conductivity contribution and low frequency polarization mechanisms at ultrasonic frequencies, which is a positive feature for the sensor development and analysis. Mechanic losses are also low and quality factor is high enough.

Evaporated electrodes and embedding in sensor can be considered as a mechanical load for the extremely soft EMFIT films and result in the decrease of parallel and serial resonance frequencies observed by the shift of *R(f)* or *G(f)* maxima respectively (see Figures 1 and 2). Taking into account the small thickness of the EMFIT films (70 µm), the resonance frequency is very low (600÷850 kHz) and correspond to the extremely low sound velocity V = 85÷120 m/s. This value is of course an effective one and reflects the inhomogeneous structure of the film. Together with the low density (ρ = 330 kg/m^3), the extremely low sound velocity results in the anomalously low acoustic impedance of the EMFIT film $Z_A = \rho V$ = 0.028÷0.040 MRayl. It is only two orders of magnitude higher than the acoustic impedance of air (Z_{air} = 0.00042 MRayl), but three orders of magnitude less than the impedance of ceramic or crystal piezoelectrics and two orders of magnitude less than the impedance of composite or polymer piezoelectrics.

Generally, EMFIT film demonstrates acceptable electromechanical properties in comparison with other piezoelectric materials (Table 1). For the air-coupled ultrasonic applications, two parameters play the major role: coupling factor and acoustic impedance. Coupling factor K defines an effectivity of the energy transformation by the ultrasonic transducers, while acoustic impedance Z_A defines the transmitting energy attenuation because of the impedance mismatch between the transducers and air. The value of $FOM = 10^4K^4/Z_A^2$ characterizes efficiency of piezoelectric materials in the air-coupled ultrasonic applications and can be used as a figure of merit [16,17]. Low coupling factor complicates the application of EMFIT film, but taking into the account the figure of merit (i.e. both important parameters, K and Z_A), EMFIT film has advantages in comparison with piezoelectric polymer film (PVDF), composites or ceramics (see Table 1)

Table 1. Properties of piezoelectric materials in comparison

Material / **Property**	**Ferroelectret film EMFIT**	**Ferroelectric polymer film PVDF**	**Ceramic (PZT) - polymer composite**	**Ceramics PZT**
Density ρ [kg/m^3]	330	1780	1000-5000	4000-8000
Dielectric permittivity [10 kHz] ε_{33}^T	1.12 – 1.23	12	50-500	150-3500
Dielectric losses [10 kHz] $tan\delta$, 10^{-3}	1	10	1-100	1-10
Coupling factor K_{33}	0.06	0.11-0.15	0.65	0.35-0.55
Quasi-static piezoelectric coefficient d_{33} [pC/N]	25 – 700* 80	20-25	50-300	70-600
Sound velocity V_3 [m/s]	85	2200	~3000	4000-6000
Acoustic impedance Z_A [MRail]	0.028	3.9	6.5	25-37
$FOM = 10^4K^4/Z_A^2$	**165**	**0.19**	**42**	**~0.6**
Operating temp. [°C]	-20…+50	...+80	…+150	…+300

*Values of the piezoelectric coefficient from literature.

Unfortunately, commercially available R-series and S-series EMFIT sensors cannot be used as the ACUS transducers. They include extra polyester layers, which suppress the thickness mode of the electromechanical resonance and shift it to the low frequencies, below 100 kHz. Even one-sided laminated electrode (with 25 μm thin polyester layer) results in significant shift of the electromechanical resonance toward low frequencies (see curve 4 in Figure 1). These results evidence a significant influence of the electrode mass on the electromechanical properties and force us to conclude that EMFIT films with laminated electrodes cannot be used in ultrasonic transducers. Therefore we focus on the electrodes evaporated directly to the EMFIT films. Evaporated electrodes also result in decrease of the resonance frequency, but it still remains above 500 kHz (Figures 1 and 2).

Both material and thickness of the electrodes influence the electromechanical properties of the EMFIT film. Increasing of the electrode thickness from 100 nm to 300 nm results in decreasing of the resonance frequency, diffusing and reducing of the resonance anomalies and in reducing of the coupling factor K_{33}. For the EMFIT films with Al 100 nm, Cr/Al 100 nm and Cr/Au 200 nm electrodes, coupling factor is the same as for the films without electrodes (K = 0.05÷0.06). In the films with 300 nm electrodes, coupling factor reduces down to K = 0.03÷0.04. Comparison of the EMFIT films with different evaporated electrodes evidences that the films with 100 nm Al, 100 nm Cr/Al and 200 nm Cr/Au electrodes show pronounced electromechanical resonance (Figure 3a, 3b) and highest coupling factor. Consequently, they are more suitable for the air-coupled ultrasound transducers. Thin Al or Au evaporated electrodes do not suppress the electromechanical properties of the EMFIT films.

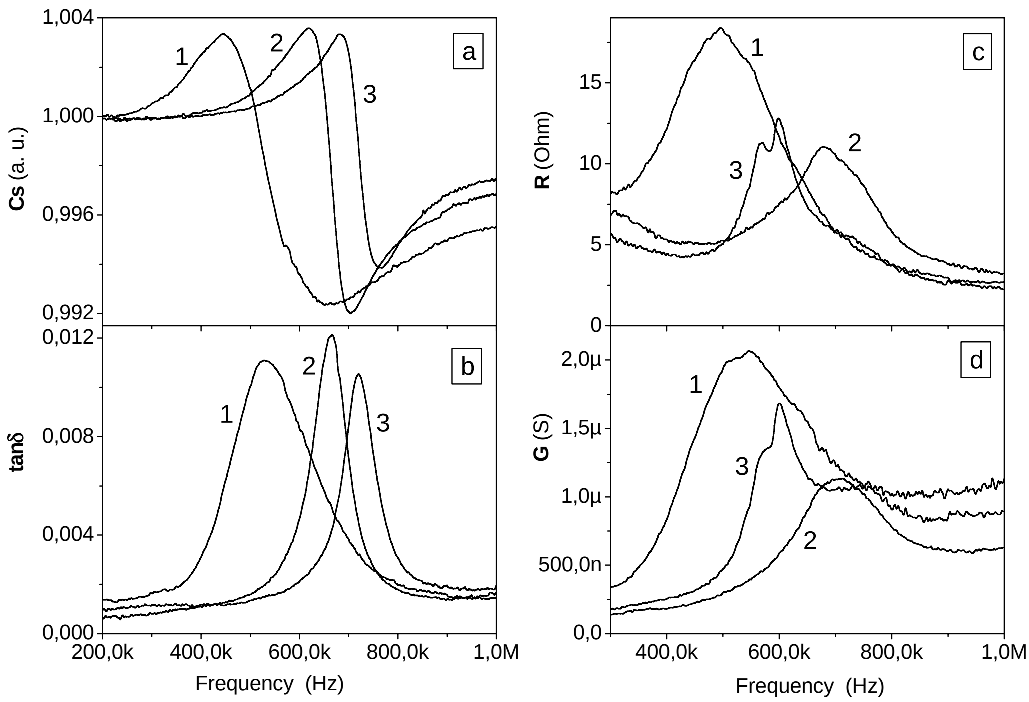

Figure 3. Comparison of EMFIT films with evaporated electrodes (**a** and **b**) and the ultrasonic sensors prepared from these films (**c** and **d**). Frequency dependences of the normalised serial capacitance C_s (**a**), dielectric losses tanδ (**b**), real part of impedance R (**c**) and real part of admittance G (**d**) of the films and sensors with evaporated 200 nm Cr/Au electrodes (**1**), 100 nm Al electrodes (**2**) and 100 nm Cr/Al electrodes (**3**).

EMFIT films with evaporated electrodes were embedded in the simple sensor described in Section 2. Embedding of the EMFIT films in the sensor results in further decrease of the resonance frequency, diffusing and reducing of the resonance anomalies (Figures 1÷3), but not in the change of coupling factor. Consequently, being embedded in the sensors, EMFIT films with thin evaporated electrodes (100 nm Al or Cr/Al and 200 nm Cr/Au) save the value of coupling factor K = 0.05÷0.06 characteristic for the free films without electrodes. Comparison of the sensors (Figure 3c, 3d) proves, that sensors with thin electrode EMFIT films show pronounced and sharp electromechanical resonance and can be considered as ultrasonic transducers.

4. Air-Coupled Ultrasonic Experiment

Prototype sensors with thin electrode EMFIT films were used as transducers in the air-coupled ultrasonic experiment (see Section 2). The experiment demonstrates high sensitivity of the EMFIT transducers. Multiple pulses, corresponding to the multiple reflections were observed in the pulse-echo mode (Figure 4a). The sequence of more than 13 pulses is well seen at 1 cm transducer-reflector distance. Both reflected and transmitted pulses can be well detected with an increase of the air path length up to 50 cm, at least (Figure 4b). The amplitude of the received pulse (A) was high enough in our setup with

60 dB amplification and decayed from ~12 V at 2 cm air path to A ~0.3 V at 46 cm air. The extinction distance $L \approx 12$ cm, estimated from our experiment, corresponds to the mean frequency of the EMFIT transducers ≈ 600 kHz.

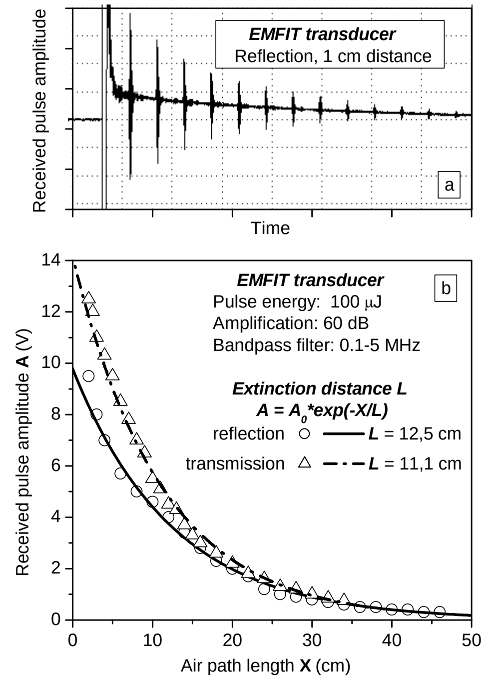

Figure 4. Air-coupled ultrasonic experiment. (**a**) Multiple pulses observed in the pulse-echo mode at 1 cm transducer – reflector distance. (**b**) Received pulse amplitude vs. air path length in both pulse-echo and transmission modes.

We replaced non-contact Ultran GN-55 transducers, used in basic configuration of the ACUS system "USPC 4000 AirTech Hillger", by our EMFIT transducers and performed volume scans of the rectangular (12×12 cm^2) polyethylene step wedge (15 mm to 10 mm thick) with a multiple holes (20 mm to 1 mm in diameter, 5 mm to 2 mm deep), shown in Figure 5a. A typical shape of the transmitted pulse is shown in Figure 5b. The same experiments were also done using Ultran GN-55 transducers. The sender – receiver distance (in the transmission mode) was 8÷9 cm and the transducer – wedge distance (in the pulse-echo mode) was 3÷4 cm in all experiments. Both amplitude (C-scan) and delay time (D-scan) images were extracted from the volume scans and are shown in Figures 5 and 6.

Generally, the amplitude and delay time images taken by EMFIT transducers in both pulse-echo and transmission modes demonstrate that non-contact ultrasonic testing with EMFIT transducers is possible. All the details are well seen, even small holes in the wedge. Steps of the wedge are also well recognisable and can be quantitatively estimated by the delay time profile (Figure 5c). We compared results obtained by EMFIT and non-contact Ultran transducers. The EMFIT scan images look more noisy than the Ultran ones. It reflects lower sensitivity of the EMFIT transducers: ~15 dB below the Ultran transducers, according to our estimation. But our EMFIT transducers are only prototypes in fact. They were developed as a measuring cell for the impedance measurements and not optimised for the transducer applications. No special electric impedance matching circuits were developed and we used the Ultran one to apply the driving voltage. It means that EMFIT transducers were not matched properly to the electric pulse generator because of the much higher input impedance comparatively to the Ultran transducers. Taking into the account all the features mentioned above, we hope that sensitivity of our prototype EMFIT transducers can be significantly improved, up to the level of piezoceramic or piezocomposite non-contact transducers.

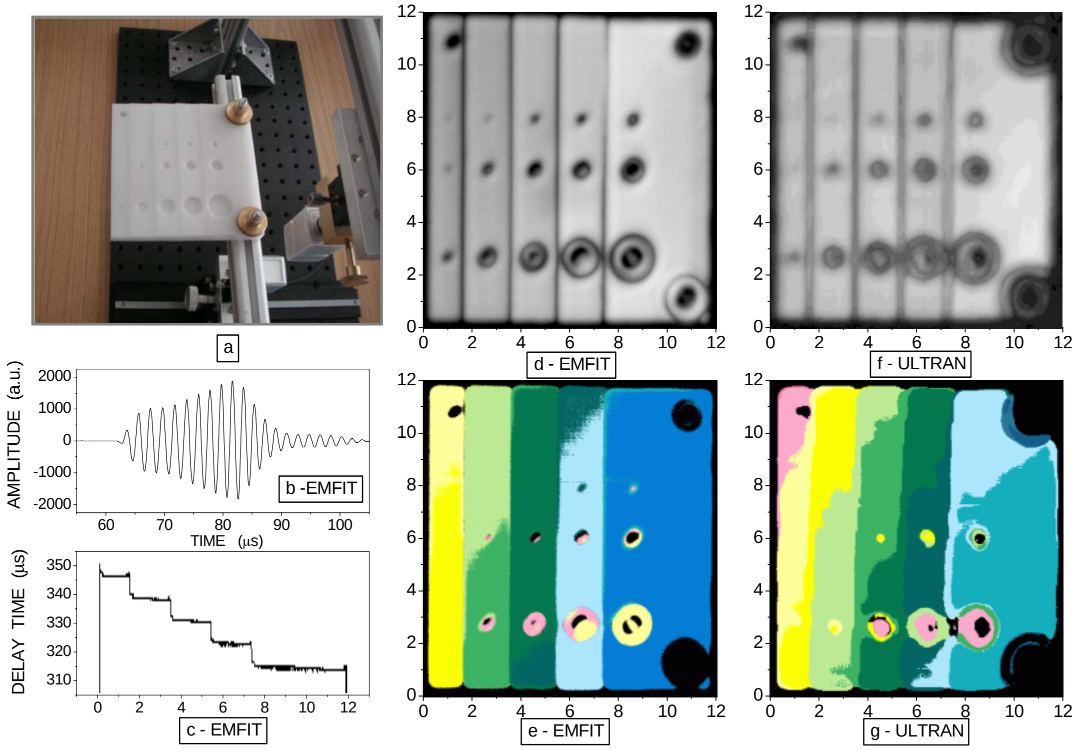

Figure 5. EMFIT and Ultran transducers in comparison (pulse-echo mode): amplitude (**d**, **f**) and delay time (**e**, **g**) images of the step wedge, obtained by EMFIT (**d**, **e**) and Ultran (**f**, **g**) transducers. (**a**) Tested polyethylene step wedge. (**b**) Typical shape of the pulse transmitted by EMFIT transducers. (**c**) Example of the delay time profile along *X*-axe in (**e**).

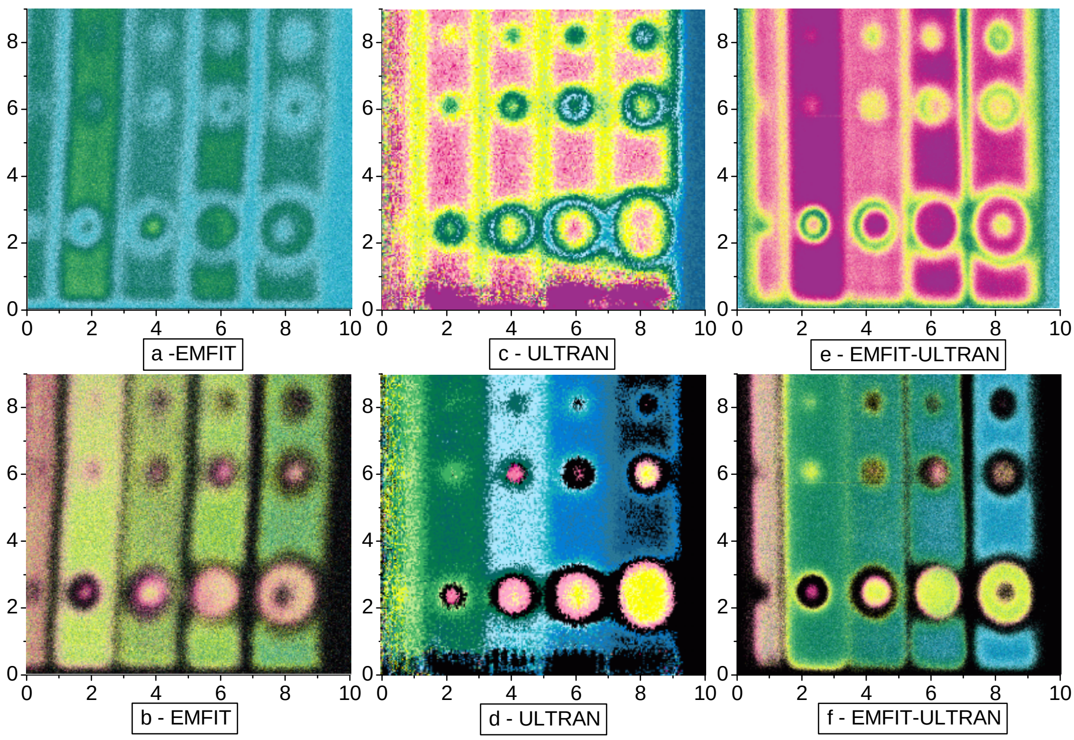

Figure 6. EMFIT and Ultran transducers in comparison (transmission mode): amplitude (**a**, **c**, **e**) and delay time (**b**, **d**, **f**) images of the step wedge, obtained by EMFIT (**a**, **b**) and Ultran (**c**, **d**) transducers, as well as by transmission from EMFIT to Ultran transducer (**e**, **f**).

Even being more noisy, EMFIT scan images contain more details and show finer features than Ultran ones. It evidence higher resolution of the EMFIT transducers which can be attributed to smaller focussed spot of the acoustic wave due to the smaller diameter and better directivity pattern. The last could be related to the different movement of the active element surface caused by the different construction of the EMFIT and Ultran transducers. More broad frequency band and different shape of the pulse can also contribute to the higher resolution of EMFIT transducers. Figures 6e and 6f illustrate perspectives of sensitivity improving of the EMFIT transducers. These images were taken by using the EMFIT transducer as a sender and the Ultran transducer as a receiver. In this way we combined higher sensitivity of the Ultran transducers and higher resolution of the EMFIT transducers and obtained less noisy images than that taken by two EMFIT transducers (Figures 6a and 6b) and more detailed images than that taken by two Ultran transducers (Figures 6c and 6d).

Our results prove that sensors, based on the EMFIT films, can be used as high frequency, high-sensitivity air-coupled ultrasonic transducers. In spite of very simple and not optimised construction, they demonstrate very promising results. Possibilities of the sensor construction optimisation and development of the films with improved electromechanical properties [14,15,21] make the air-coupled ultrasonic application of cellular ferroelectret films a real perspective.

5. Conclusions

Our impedance spectroscopy study of the commercially available EMFIT films reveals acceptable electromechanical properties for the air-coupled ultrasonic applications: high-frequency electromechanical resonance (thickness mode above 500 kHz), very low acoustic impedance Z_A = 0.028÷0.040 MRayl, low dielectric and mechanic losses, absence of dielectric dispersion out of the electromechanical resonance. Low coupling factor K = 0.06 complicates the application, but taking in to the account both important parameters, K and Z_A, EMFIT films have advantages in comparison with PVDF films or piezoelectric composites. It was shown, that additional laminated polyester layers suppress the electromechanical resonance. Consequently, commercially available R-series and S-series EMFIT sensors and films with laminated electrodes cannot be used in ultrasonic transducers. Influence of the electrodes, evaporated directly to the EMFIT films, on the electromechanical properties was investigated. Electron beam evaporation technology was adapted to the EMFIT films to prepare samples with Au and Al electrodes without reducing or suppressing of the electromechanical properties. ACUS transducers, based on the EMFIT films with thin evaporated Al and Au electrodes, were developed and tested. In spite of the simple construction, high sensitivity of the EMFIT transducers was proved in the ACUS experiment. Both reflected and transmitted pulses were detected through the air path length up to 50 cm. EMFIT transducers were used as a sender/receiver of the ACUS system “USPC 4000 AirTech Hillger”. Amplitude and delay time scanned images of the inhomogeneous relief object (polyethylene step wedge with holes), obtained in both pulse-echo and transmission modes, demonstrate that non-contact ultrasonic testing with EMFIT transducers is possible.

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References

1. J. Krautkrämer, H. Krautkrämer „Werkstoffprüfung mit Ultraschall“, Berlin, Springer, 1986, 708p.
2. M. C. Bhardwaj, "Non-Destructive Evaluation: Introduction of Non-Contact Ultrasound", in "Encyclopedia of Smart Materials", Ed. M. Schwartz, John Wiley & Sons, New York, 2001, 690-714.
3. E. Blomme, D. Bulcaen, F. Declercq “Air-coupled ultrasonic NDE: experiments in the frequency range 750 kHz – 2 MHz”, NDT&E International, 2002, **35**, 417-426.
4. W. Hillger, F. Meier, R. Henrich “Inspection of CFRP Components by Ultrasonic Imaging with Air Coupling”, NDT.net, 2002, **7**, No.10.
5. T. H. Gan, D. A. Hutchins, D. R. Billson “Preliminary studies of a novel air-coupled ultrasonic inspection system for food containers”, J. Food Engineering, 2002, **53**, 315–323.
6. E. Blomme, D. Bulcaen, F. Declercq “Recent observations with air-coupled NDE in the frequency range of 650 kHz to 1.2 MHz”, Ultrasonics, 2002,**40**, 153–157.
7. T. H. Gan, D. A. Hutchins, D. R. Billson, D. W. Schindel “The use of broadband acoustic transducers and pulse compression techniques for air-coupled ultrasonic imaging”, Ultrasonics, 2001, **39**, 181–194.
8. “Modern Ultrasonic Transducers”, www.secondwavesystems.com
9. “Piezoelectric Materials in Devices”, ed. N. Setter, Lausanne, EPFL, 2002, 518p.
10. G. S. Neugschwandtner, R. Schwoediauer, M. Vieytes et al. "Large and broadband piezoelectricity in charged polypropylene foam electrets", Appl. Phys. Letters, 2000, **77**, 3827-3829.
11. Neugschwandtner, G. S., Schwoediauer, R., Bauer-Gogonea, S.; Bauer, S. "Piezo- and pyroelectricity of a polymer-foam space-charge electret", J. Appl. Phys, 2001, **89**, 1-9.
12. “EMFIT film specifications”, www.emfit.com.
13. S. Bauer, R. Gerhard-Multhaupt, G. M. Sessler “Ferroelectrets: Soft Electroactive Foams for Transducers”, Physics Today, 2004, **57**, 37-43.
14. M. Wegener, W. Wirges, R. Gerhard-Multhaupt et al. "Controlled inflation of voids in cellular polymer ferroelectrets: Optimizing electromechanical transducer properties", Appl. Phys. Lett., 2004, **84**, 392-394.
15. M. Dansachmüller, R. Schwödiauer, S. Bauer-Gogonea et al. “Elastic and electromechanical properties of polypropylene foam ferroelectrets”, Appl. Phys. Letters, 2005, **86**, 031910.
16. J. Döring, J. Bartusch, A. Erhard, V. Bovtun „Eigenschaften von Polypropylen- und PVDF-Folien für Luftschall-Anwendungen“, DACH - Jahrestagung 2004 Salzburg, www.ndt.net/article/dgzfp04/papers/p11/p11.htm.
17. J. Döring, V. Bovtun, J. Bartusch, U.Beck, A. Erhard, Y. Yakimenko „Air-coupled ultrasound sensors based on the cellular polypropylene ferroelectret films: impedance spectroscopy study”, submitted to Ultrasonics
18. “S-series sensors specifications”, www.emfit.com.
19. “R-series sensors specifications”, www.emfit.com.
20. J. Beckmann, J. Bartusch, J. Döring, A. Erhard, U. Ewert, U. Zscherpel "Time domain spectroscopy techniques for non destructive contact less flaw detection and imaging in advanced materials”, ECNDT 2006 Berlin, manuscript CD, P190.
21. M. Wegener, W. Wirges, J. Fohlmeister, B. Tiersch, R. Gerhard-Multhaupt, “Two-step inflation of cellular polypropylene films: void-thickness increase and enhanced electromechanical properties”, J. Phys. D: Appl. Phys., 2004, **37**, 623–627.