A Fabrication Procedure for Airborne Ultrasonic Phased Arrays Based on Cellular Electromechanical Film

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Abstract—In this work, a novel procedure that considerably simplifies the fabrication process of ferroelectret-based multi-element array transducers is proposed and evaluated. Also, the potential of ferroelectrets as active material for air-coupled ultrasonic transducer design is demonstrated. The new construction method of multi-element transducers introduces two distinctive improvements, first, the active ferroelectret material is not discretized into elements and, second, the need of structuring upper and lower electrodes in advance of the permanent polarization of the film is removed.

In order to validate the procedure, two linear array prototypes of 32 elements were built and evaluated. A low crosstalk among elements, below -30 dB, was measured by interferometry. Likewise, a homogeneous response of the array elements, with a maximum deviation of ±1.8 dB, was obtained. Acoustic beam steering measurements were accomplished at different deflection angles using a calibrated microphone. The ultrasonic beam parameters, namely lateral resolution, side lobes level, grating lobes and focus depth, were congruent with theory. The proposed procedure simplifies the manufacturing of multi-dimensional arrays with arbitrary shape elements and not uniformly distributed. Furthermore, this concept can be extended to non-flat arrays as long as the transducer substrate conforms to a developable surface.

I. INTRODUCTION

Array technology is widely used in ultrasonic applications, due to its capability for electronically focusing and steering an ultrasound beam at different depths and angles without moving the transducer mechanically. Well known phased array technologies used in ultrasonic imaging involve piezoelectric crystals, ceramics, polymers, piezo composites and capacitive devices. Some air-coupled NDT applications have been attempted using piezoelectric ceramics and polymer-membrane capacitive arrays [1]. In these cases, the high acoustic impedance mismatch, the slow propagation velocity and the high attenuation have prevented a more widespread use.

Recently, new array transducers based on ferroelectrets have been introduced, which exploit the special transducer properties of these materials. Metzger et al. propose the use of the ferroelectret films to monitor shelf stocks by weight sensing of goods [2]. Degel et al. [3] built a linear array of 32 elements and 0.5 mm pitch for airborne ultrasound showing preliminary characterization results.

In this work we propose a novel fabrication process to build ferroelectret-based array transducers. Our approach has two main differences regarding the previously reported works. Specifically, a) the polymer film is not discretized into elements, as it is done in [2], and b) the totality of cellular film used in the array transducers construction is permanently polarized, which considerable simplifies the fabrication process compared with [3]. After characterization measurements, the new procedure, based on a previously charged cellular polymer film, has proved to be easy, inexpensive and reliable. This allowed attaining a very low inter-element crosstalk and a wide bandwidth, without sacrificing sensitivity.

A. Ferroelectrets: The Electromechanical Film EMFi

Basically, a ferroelectret is a cellular polymer foam electret with an internal space-charge. Its inner cellular structure is constituted by voids whose upper and lower surfaces are oppositely charged. As a consequence, an electrical signal results from changes of the dipole sizes when mechanical stress is applied. Reciprocally, a variation of thickness is produced upon application of an external electric field. That is, the physical principle for the behavior of ferroelectrets essentially differs from that of polar ferroelectric polymers [4]. In this work, we have used the commercially available electromechanical film Emfit, type HS-03-20BRAL1 (Emfit Ltd., Vaajakoski, Finland). The film consists of a central PP(Polypropylene)-based foam layer surrounded by two 10-μm-thick solid PP skin layers. One of these layers is coated with aluminum to operate as the upper electrode. The thickness of the film is approximately 70μm. The lateral dimension of voids may vary from 10 μm to 100 μm whereas the average height is around 3 μm [5].

Emfit film operates in thickness mode when an external voltage is applied between its faces. Furthermore, its piston-like response is not influenced by substrate geometry, provided
it conforms to a developable surface [6]. Due to its capacitive characteristic, it can be operated either in actuator mode or sensor mode and exhibits reciprocal behavior. In addition to this, a large usable frequency range from 20 to 300 kHz, a good matching with the air impedance and an ease of use and manipulation compared to other technologies, make Emfit film an excellent candidate for air-coupled ultrasonic applications [7] [8].

II. MATERIALS AND METHODS

A. Experimental Setup

The experimental setup used in this work mainly consists of three subsystems, namely, the transducer excitation equipment, the controlled motion units and the measurement devices. In order to form the beam, a commercial phased array system is used (SITAU 32-128, Dusel SL, Madrid, Spain). This allows us to handle array prototypes of up to 128 elements with a maximum number of 32 active channels.

With regard to the measurement of the acoustic field, the mechanical displacement and rotation units enable us to sample the beam at arbitrary observation points within the X-Z plane. The acoustic measurements are carried out using a calibrated microphone (Brüel & Kjær 1/8” 4138), which is carefully oriented perpendicular to the observation plane in order to minimize the effect of its directivity on the pressure measurement. In the SITAU system, a focal law is set up to focus and steer an emitted beam on a point in the X-Z plane. Array elements are excited with the focal law delays, simultaneously providing a trigger signal to the oscilloscope that records the complete time signal at a given observation point. As the experimentation was not conducted in an anechoic chamber, special care was taken to avoid reflections from close objects.

The surface velocity of the transducers is measured by means of a laser doppler vibrometer from Polytec GmbH (Waldborn, Germany) which is located on an antivibratory table and has a maximum velocity resolution of 0.5 μm/s.

B. Fixation of the film

The use of plastic adhesive tapes for sticking the film on a substrate has recently been reported [6]. In that work, different monoelement transducers were fabricated using an isotropic XYZ conductive plastic tape (ECPT) to fix the Emfit film on a given surface. It was concluded that plastic tapes with acrylic adhesive behaves as a rigid substrate. Consequently, the vibratory response of the active area is not affected by the tape, as long as special care is taken to avoid good adhesion and avoid creases.

Here, we have used a special double-faced adhesive tape, that is electrically conductive only through its thickness, to stick the Emfit film on a substrate. Its internal structure is constituted by an acrylic matrix filled with conductive particles which allow the interconnection between substrates. Table II-B lists the typical physical properties of this Z-axis conductive tape (ZCPT) given by the manufacturer (3M, St. Paul, MN, USA).

### TABLE I

<table>
<thead>
<tr>
<th>Physical Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulation Resistance(^1)</td>
<td>3.4×10(^{-14})Ω/m/Boxempty</td>
</tr>
<tr>
<td>Adhesive Type</td>
<td>Acrylic</td>
</tr>
<tr>
<td>Thickness</td>
<td>50 μm</td>
</tr>
<tr>
<td>Minimum Free Space between conductors(^2)</td>
<td>0.4 mm</td>
</tr>
<tr>
<td>Minimum overlap area (^3)</td>
<td>3.2 mm(^2)</td>
</tr>
<tr>
<td>Interconnect Resistance(^3)</td>
<td>0.2 to 5 Ω</td>
</tr>
</tbody>
</table>

\(^1\) Based upon ASTM D-257.
\(^2\)Space recommended to ensure electrical isolation. Customer may qualify finer pitch performance in their applications.
\(^3\) Performance values depend upon the the application design and the substrates to be bonded.

C. Array Prototypes Description

We have tested two linear array prototypes of 32 elements. The inter-element spacing (d) of both arrays is 3.43 mm (1340 mils) which approximately corresponds with a unit wavelength at 100 kHz in air. Both prototypes have a full aperture 108.8 mm width and a height of ten times d. The only difference between the two array probes is in the size of the gap between adjacent elements (g). Values of 1 mm and 1.524 mm were chosen to ensure electrical isolation following the ZCPT manufacturer requirements. If the element width becomes too small, the non-homogeneity of both, the Emfit and the ZCPT, might yield an irregular distribution of the element sensitivity and even to faulty elements. For this reason and bearing in mind that the nominal lateral dimension of the Emfit air voids can be as high as 100 μm, we have considered, as a rule of thumb, that an element width (w) greater than five times this figure would be appropriate. As a result, the pitch (d = w + g) should always be greater than 1 mm in order to gain advantage of the ZCPT characteristics. At present, further investigation is being conducted in order to precisely state the actual dimensional constrains in the array transducers fabricated with Emfit film and ZCPT.

III. THE PROPOSED FABRICATION PROCEDURE.

Recently, array transducers based on piezoelectric cellular polymers have been introduced by Metzger et al. [2] and by Degel et al. [3]. The former shows the feasibility of a foam-based pressure-sensitive network designed to monitor shelf stocks by cutting the original ferroelectret film into smaller square elements. The latter reports preliminary characterization results for a 32 elements ultrasonic array intended for airborne applications. Degel’s fabrication process is comprised of two stages, namely, structuring the upper and lower electrodes on both sides of a non polarized cellular film by means of sputtering and etching techniques, and subsequently charging the active area of the aperture using a corona discharge, among other poling methods. This procedure leads to an elaborated manufacturing process, requiring expensive and specialized instrumentation. Despite of the promising results, difficulties are reported with regard to the sensitivity distribution of the array elements, faulty elements and electromechanical crosstalk.
In view of this, we propose a fairly easier fabrication approach to build array transducers, which works with any already polarized polymer cellular film. In our construction process, the sheet of Emfit film is cut to a single rectangular piece with the size of the intended array full aperture. The individual element lower electrodes are created with copper pads of a printed circuit board. In order to complete the array, the non-metalized side of the Emfit film piece is then stuck on the lower electrodes deployment, using ZCPT. (Figure 1). Finally, the aluminum side of the Emfit piece is used as a common upper electrode which is connected along the whole length of the ground copper pad using a cooper tape. The major advantage of this procedure lie in the way the full aperture is discretized in elements since the end-user is neither required to cut the individual elements to size and shape, nor structuring the electrodes on a non-polarized cellular polymer film, as in the preceding approaches.

Due to a combination of the conductive properties of the adhesive, only in the axial direction (Z), and the low deformation of the Emfit material in the lateral direction, a very high electrical and mechanical isolation is achieved between electrodes, resulting in low crosstalk. Thus, the fabrication method permits a very precise control on the shape of the lower electrodes of the array in an easy and inexpensive way. This also opens up the possibility of fabricating non-uniform arrays and consequently validating their design methods, which is a current research interest. Furthermore, the process can also be employed for array transducers built on any developable surface using, in this case, flexible printed circuit boards.

IV. EXPERIMENTAL RESULTS.

In this section, the proposed fabrication procedure is evaluated. The performance of a 32-element array prototype is presented; experimentation results with regard to the element sensitivity distribution and inter-element crosstalk are given. Subsequently, beam steering pattern measurements were carried out and compared with theory.

A. Element Sensitivity Distribution

For both array prototypes a homogeneous sensitivity distribution is observed; showing a maximum element acoustic deviation of $\pm 1.8$ dB. Furthermore, no faulty elements were found. Differences in the element responses are mainly due to the non-homogeneities in shape, size and charge, of the inner cavities of the Emfit film, as well as, variations in the Z-conductive tape adhesion.

B. Crosstalk Level Measurement

With the aim of quantifying the level of inter-element crosstalk, 20-pulse sine bursts at single frequencies ranging from 30 kHz to 350 kHz were exclusively applied to the element number 16. Subsequently, its velocity response and that of the inactive adjacent element 17 (grounded), were captured. The frequency increment was set to 10 kHz and measurements were taken at 10 different points along the whole length of each element. Figure 2 shows the obtained results. Crosstalk was measured to be lower than -40 dB at frequencies below 250 kHz, which is comparable to that reported for other array technologies, such as piezocomposites [9]. Beyond that frequency, the crosstalk level grows up to -20 dB for both array probes. Also, the standard deviation increases with frequency, which is directly related to the non-homogeneity of the velocity profile in a monoelement transducer at frequencies near resonance.

The observed dependency of the crosstalk on frequency corresponds with a capacitive coupling between elements, which can be attributed to parasitic capacitances due to the proximity among PCB tracks and lower electrodes. In principle, measured crosstalk is not mechanical in origin since, otherwise, some delay between the two element responses would be appreciable due to the rather small sound wave propagation velocity in PP [10]. Direct observation of the time waveforms of the surface velocity of the excited element and its neighbor showed no appreciable delay between them. However, further investigation is required in order to measure and model the surface wave propagation in charged cellular polymers such as the Emfit film.

C. Beamforming

Each element was excited with a burst of 3 square pulses at 100 kHz. Delays of the electronic signals for each element of the array were calculated to focus the beam at 200 mm depth, and a deflection angle of 30° was used. The acoustic signal generated by a single element was previously acquired to adjust the simulation model parameters.

Results are shown in Figure 3. Experimental data highly agrees with simulation at all depths and angles. Main lobe width, side-lobe levels and focus depth are in accordance with the theoretical calculations for the array geometry and excitation frequency. Peak-to-peak pressure at the focus was measured to be 7.3 Pa. Grating lobes angular position and peak amplitude are also as theoretically predicted.
minimum free space between conductors of the ZCPT.

Therefore, further research is being conducted in order to output that tightly follows the expected behavior by simulation.

array prototypes of 3.43 mm of pitch, exhibiting an acoustic element gap or the element width, has allowed us to fabricate size of the inner charged air voids, compared to either the inter-element crosstalk in ultrasound arrays,

Fig. 2. Crosstalk level of the film’s surface velocity measured between elements 16 and 17 of the array prototype 1, obtained from interferometric measurements at 10 different surface points along the length of each element. Element 16 active.

Fig. 3. Beam pattern, focus at 200 mm and steering angle of 30 degrees. (Upper-Left) Simulation results, 35 dB dynamic range. (Upper-Right) Measured beam pattern, 35 dB dynamic range. (Down) Lateral pattern at 200 mm.

V. DISCUSSION AND CONCLUSIONS.

In this work, the potential of a new procedure to fabricate ferroelectret-based airborne ultrasonic arrays has been demonstrated. The measured low inter-element crosstalk, along with the homogeneous element sensitivity distribution yield to an array response in fairly good agreement with theory. The small size of the inner charged air voids, compared to either the inter-element gap or the element width, has allowed us to fabricate array prototypes of 3.43 mm of pitch, exhibiting an acoustic output that tightly follows the expected behavior by simulation. Therefore, further research is being conducted in order to state the minimum permissible pitch and its dependency on the nominal size of the inner voids of the Emfit film and the minimum free space between conductors of the ZCPT.

So far, several 32-element array prototypes are being developed with a pitch of less than 1 mm (half a wavelength at 150 kHz in air), but some issues as mechanical crosstalk and element sensitivity distribution must be evaluated. These prototypes include 32 pre-amplifiers in the same PCB which supports the Emfit array, making it possible to obtain acoustic images with full aperture in pulse-echo mode.

In conclusion, the proposed fabrication method has proved to be simple, inexpensive and reliable, opening up the possibility of building multidimensional arrays for air-coupled applications, which exploit the electromechanical acoustical properties of the Emfit film, i.e. high $d_{33}$ coefficient (≈ 250 pC/N), good adaptation to air (acoustic impedance of ≈0.03 MRayls), wide usable frequency range of operation (30–350 kHz), high mechanical flexibility due to its cellular structure and easiness of manipulation. Two-dimensional arrays can be easily implemented and also 3D configurations are allowed as long as the array substrate conforms to a developable surface. The actual size and shape of the individual elements can also be easily customized by structuring the lower electrodes on an either standard or flexible printed circuit board. This fact is of noticeable importance to the design methods of sparse/non-uniform arrays and their experimental validation, which is currently of increasing interest.

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REFERENCES