64 Elements two-dimensional piezoelectric array for 3D imaging

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Abstract

Ultrasound has a large potential on non-invasive inspection with main applications in medical imaging and non-destructive testing (NDT). The increasing interest in 3D imaging applications leads to investigate new solutions for two-dimensional (2D) ultrasonic arrays with an affordable number of electronic channels without resolution degradation. 2D segmented annular arrays (SAAs) are a good compromise between resolution—image quality—and number of electronically active channels. A 1–3 piezoelectric composites are used as basis material to manufacture the array transducers due to their low planar coupling and high electromechanical coupling coefficients.

A 1.5 MHz SAA of 64 elements and 20 mm of diameter was designed, manufactured and tested. The design key point is the use of a flexible circuit with electrodes and tracks that define the array geometry. The piezocomposite was used as a monolithic support. Soft backing and one matching layer were used. The array elements have been tested electrically and acoustically showing good agreement with a KLM-based simulation model. Acoustical field measurements in water at different steering angles were made and compared with simulations performed with a model that uses an exact solution of the impulse response approach. Side lobes are important because the array geometry used was designed to work in metals for NDT purposes. Smaller array elements should be made for medical applications. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Piezocomposite; Two-dimensional array; 3D imaging; Cross-coupling; Ultrasonic beam pattern

1. Introduction

The generation of ultrasonic images for non-destructive testing (NDT) applications and medical imaging needs the development of two-dimensional (2D) array transducers. Until now, the commercial systems are \( N \times N \) square apertures. The main drawback of this design is the huge number of transducers needed to maintain good resolution at the two imaging planes—elevation and azimuth. To overcome this problem, sparse techniques have been proposed to decrease the number of active elements until an affordable number [1]. Segmented annular arrays (SAAs) are a quite promising solution. Their circular symmetry, lower periodicity and spatial diversity are in the origin of their good image performances (low side lobes), which enables the generation of 3D images of good quality with reduced number of elements in comparison with conventional 2D square array transducers [2].

2. Array fabrication

To check the image performance of SAA transducers, a 1.5 MHz sample was designed, fabricated and tested. Fig. 1 shows the fabrication outlines of the SAA and the array geometry used in this work. The key point of the design is the use of a flex circuit (0.03 mm copper and 0.02 Kevar) with the array geometry and tracks for the wire connections. The piezoelectric substrate is a 1–3 piezocomposite made with PZ27 piezoceramic (Ferroperm) and Araldit D (Ciba & Geigy) following standard dice-and-filling manufacturing procedures. The pitch of the composite is 0.3 mm. The flex circuit was carefully bonded on the piezocomposite substrate with a non-conductive epoxy [3]. The critical stage is the stress...
applied during the bonding process because the thickness of the glue creates a spurious capacity that degrades the transduction performance. Table 1 shows the simulated effects on the electromechanical coupling of a single array element for different glue thickness. In the same table, measured values obtained with two samples bonded at different pressing conditions are also shown. The bonding thickness was measured by differential thickness measurements. The results show how critical is the bonding stage.

A thin ground silver electrode was sputtered over the composite emitting surface. One \( \lambda/4 \) matching layer and light backing were used. As a final step the entire array was placed into a metallic housing.

3. Array characterisation

The piezocomposite properties were calculated using the Smith model [4], and an one-dimensional transducer model based on the KLM approach [5] was used to simulate the electrical and acoustical array element performances taking into account all the mechanical and piezoelectric sections—backing, flex circuit, composite, matching layer. Electrical and acoustical transducer losses were taken into account for simulations.

The actual behaviour of the array elements was tested in the frequency domain measuring the input electrical impedance with a HP 4194A Impedance Analyser under air and water loading conditions. Time domain tests were also made measuring the impulse response in water loading using a Panametric 5052 UA Ultrasonic Analyser. The pulse shape of all the array elements was similar, varying the peak-to-peak amplitude less than 10% with respect to the media. Only three elements have a pic-to-pic amplitude value 50% lower than the media. The emitted pulse was measured with a PVDF needle hydrophone—Medisonics MkII.

Special attention was given in the characterisation of the cross-coupling between the array elements. First, gain/phase measurements in the frequency domain were performed using the gain/phase module of an Impedance Analyser HP 4194A. The test consists in comparing the output voltage generated by the travelling coupled wave at each array element—test channel—with the input voltage applied on a reference element—input channel. Fig. 2 shows the cross-coupling measured for the first three consecutive neighbours of a reference element belonging to the external ring. The main coupled modes appear at 650 kHz, 1.350 and 1.9 MHz. After three elements from the reference one, the coupled signal is lower than 60 dB.

A second test, that is conceptually the same as the previous one, was performed in the time domain. One element of the external ring was excited using a high voltage pulser—Panametric 5900 P/R—recording the signal received by the consecutive elements in the ring. Fig. 3 shows the temporal lines corresponding to three consecutive elements. The two most important coupling

![Fig. 1. Scheme of the fabrication outline and geometry of a SAA.](image)

![Fig. 2. Cross-coupling between neighbour elements of the external ring. Gain measurement using the signal applied to the reference transducer as input signal. (a) First neighbour, (b) second neighbour and (c) third neighbour.](image)

Table 1

<table>
<thead>
<tr>
<th>Epoxy thickness (( \mu \text{m} ))</th>
<th>( k_t ) simulated and real</th>
<th>Simulated</th>
<th>Measured</th>
</tr>
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<tbody>
<tr>
<td>Co</td>
<td>0.56</td>
<td>0.55</td>
<td></td>
</tr>
<tr>
<td>Co and FC 1</td>
<td>0.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Co and FC 3</td>
<td>0.46</td>
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<tr>
<td>Co and FC 5</td>
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<td></td>
</tr>
<tr>
<td>Co and FC 10</td>
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</tr>
<tr>
<td>Co and FC 15</td>
<td>0.31</td>
<td>0.30</td>
<td></td>
</tr>
</tbody>
</table>

Co: composite; FC: flex circuit.
waves travelling through the array elements can be clearly observed.

Fig. 4 quantifies the cross-coupling in the array external ring for the lowest frequency mode (650 kHz) in function of the element position. Number 1 is the nearest element to the reference transducer. Cross-coupling amplitudes decrease rapidly with the element position in the ring, increasing again as the element approaches the active element.

Another test in the time domain was performed, exciting one array element and scanning radially the array surface with a PVDF needle hydrophone using a shallow oil film as couplant. This test permits an accurate measurement of the wave velocity of the different modes propagating through the array surface, permitting to identify the different modes using the dispersion curves of the Lamb waves for this composite structure. Two waves of velocity 2136 m/s (Lamb wave) and 1500 m/s (transverse wave) respectively were identified.

4. Acoustic field test

The acoustic field was also studied, exciting the array rings independently or combined in different configurations. The transducer was placed into a water tank performing 3D scans with a PVDF needle hydrophone Medisonics MkII—flat response up to 10 MHz—driven by a computer controlled mechanical device.

As a first step before carrying out the acoustical field simulation, individual test on all the array elements were made to record the acoustic pulse shape amplitude needed for the field simulation and to test the vibration homogeneity. Fig. 5 shows the vibration pattern of the array surface for the double ring configuration formed by the two inner rings excited in parallel. Differences in vibration amplitude are less than 2 dB. Only three elements are missed.

Then, using the spatial impulse response approach, the acoustic field was computed for several focussing conditions [6]. Simulated results for the double ring configuration are presented in Fig. 6 compared with the experimental measurements performed with a 32 channel programmable pulser. The focussed pressure amplitude at a plane situated 100 mm from the array
plane and at three different elevation angles (\( \theta_F = 10^\circ, 15^\circ, 20^\circ \)) are presented. The figure shows good agreement between simulation and measurements. The side lobes are important because the ratio element pitch/wavelength is much higher than 1. The same simulations were made when the ratio between the elements pitch and the wavelength are more useful for imaging purposes. Acoustic media with higher acoustic velocity were used. Fig. 7 shows a comparison between the simulation of the transmitted acoustic field of the full array focusing at 100 mm from the array with an steering angle of 30° in the case of: (a) water (\( \lambda = 0.8 \) mm) and (b) steel (\( \lambda = 3.4 \) mm). As it can be seen, when the wavelength is higher than the array element pitch, grating lobes with amplitude 20 dB down the main lobe are achieved showing the usefulness of the proposed transducer geometry.

5. Conclusions

A SAA of 64 elements was designed, manufactured and tested. The used frequency (1.5 MHz) number of elements and aperture were chosen to work with good resolution performances for NDT imaging in metallic materials. The electrodes area was made using a flex cooper circuit bonded on a standard 1–3 piezoelectric composite. The array incorporates backing and one matching layer. The array elements were tested electrically and acoustically showing good agreement
with standard one-dimensional piezoelectric transducer models. A maximum element to element cross-coupling of $-40 \text{ dB}$ has been measured between first neighbours, decreasing rapidly.

Radiation field of the SAA was simulated and measured at different steering angles to study the side lobes intensity. The measurements were performed in water, and so lobes have significant importance as simulations predicts. The present array pattern is only valid for NDT imaging purposes. The design of other geometries with smaller array pitch will make these arrays valid for medical imaging purposes.

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**References**


