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The Role of Additive Manufacturing Technology in the Design of Sparse Transducer Arrays

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***Abstract*—Large two-dimensional (2D) arrays offer very promising prospects as an analysis tool due to their capability to obtain information of volumetric spaces. However, this kind of development has major drawbacks. The main challenge comes from the large number of elements required to achieve an acceptable image quality. The sparse arrays have been proposed as a compromise solution between the number of active elements and dynamic range. Although we can find in the literature a lot of examples about sparse arrays models, there is a significant lack of experimental prototypes. The main reason for this is that the manufacturing process is expensive and complex. In order to address this problem, the capabilities to develop structural parts of sparse arrays of manufacturing process based on Additive Manufacturing technology have been analyzed in this paper.**

***Index Terms*—sparse array, additive manufacturing**

I. Introduction

Nowadays, it is widely accepted that large two-dimensional (2D) arrays offer very promising prospects as an analysis tool due to their capability to obtain information of a volumetric space. However, to avoid grating lobe formation, the distance between transducers in the array element distribution is limited to $\lambda/2$. Therefore, large 2D matrix apertures involve a high number of elements. This issue leads to some challenges at several levels: (i) manufacturing level, because the large number of elements involves also cables, shield, matched filters, etc; (ii) signal conditioning level, because the small size of the elements, the contribution of individual elements is very low and offers poor SNR (low radiation area and low sensitivity); (iii) system control level, because of the complexity of acquiring, processing and managing a large volume of data; and finally, (iv) the economic level, because of the high cost associated with the transducer and the systems.

Although, micromachined and microelectronic manufacturing techniques reduce some of the manufacturing problems, allowing the development of high densely populated apertures [1], some of the challenges identified are still unsolved or involve a huge bunch of resources. In any case, some solution to these issues involves a high cost and a high degree of uncertainty that makes it difficult to be justified.

Consequently, there is a reduced offer of both commercial 2D transducer and associated instrumentation. Furthermore, the systems identified in the literature are mainly laboratory instruments. In this sense the reduction of active elements in the aperture, by sparse array design is an interesting solution for the development of volumetric imaging systems. Therefore, the main challenge in array design is determined by the number of elements necessary to achieve acceptable image quality. In the literature we can find a lot of examples of sparse arrays [2], [3]. However, the number of experimental prototypes is very low [4]. The main reason for this is that the manufacturing process is expensive and complex.

In order to address this problem, the capabilities to manufacture structural parts of sparse arrays based on Additive Manufacturing technology [5] and the consequences in the transducer behavior have been analyzed in this paper. The results show that Additive Manufacturing gives an opportunity to array designers to develop low cost and risky proof of concept.

II. Sparse Arrays designed for prototyping

At first, a sparse array is designed to accomplish the specifications, which are related to lateral resolution, dynamic range or number of active elements. However, in order to develop a solution suitable for manufacturing some other consideration should be done, like cable distribution and the supporting structure. In this sense it is important also take in account the manufacture procedure that is going to be followed.

Fused Deposition Modeling (FDM) techniques are suitable to produce cost-effective structural components. The materials used by these techniques are plastics that can be manipulated easily and, in order to implement arrays, show interesting mechanical properties. For this case we have considered acrylonitrile butadiene styrene (ABS), polylactic acid (PLA) and thermoplastic polyurethane (TPU).

Nowadays, 3D printers have good link with Computer Assisted Design tools that help to design tridimensional structures. Basically, the arrays element is constituted by three components: the piezoelectric component, the cable that provides electrical connection and the backing.

A. Array element structure

The Figure 1 describes the structure of a single element. The manufacturing process is divided in two stages printed as separated parts. The first stage is where the piezoelectric component, the cable and the electric contact are located. The

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manipulation degree required at this stage is very high. In the second stage, the main part of the backing structure is placed, optionally including a dispersal space.

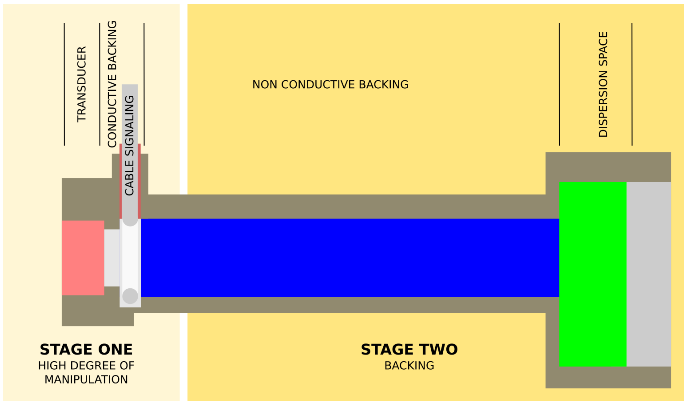

Fig. 1. Array element structure. It is divided in two stages

Two piezoelectric component have been considered for the testing purposes: 1 MHz PZ27 ceramic (Ferroperm™) and 1.5 MHz 1-3 piezocomposite (Smartmaterials™, 851 material, Dice and Fill 65%). These two components were diced in order to achieve the element dimensions and their electrical impedances were evaluated (see Figure 2). The results show that piezocomposites maintain its resonance response meanwhile the PZ27 has reduced its resonance frequency.

The cable is located near to the element and guided through a channel across the aperture structure to the outer shell of the plastic structure. To place it, we made use of supporting point and heat to fix it. In order to make contact between both elements, conductive epoxy was used. This epoxy layer constitutes the first part of the backing structure. Therefore, backing epoxy is doped with tungsten to match the impedance of the conductive layer. If the backing column needs to be more loaded, conductive epoxy could be replaced by silver conductive paint.

The material used to manufacture the first stage can be used to minimize the mechanical crosstalk between elements. In general, all materials used (ABS, TPU and PLA) show good mechanical response. However, TPU is less capable to avoid lateral oscillation. ABS has been discarded because of the wide use of acetone to clean epoxy.

III. Spiral Sparse Arrays

To analyze the capacities of FDM to develop structures capable of enclosing a dispersed matrix, a simple set of specifications have been considered as proof of concept: lateral resolution less than 1.5°, no more than 64 elements, operation frequency of 1.5 MHz and a dynamic range higher than 30 dB.

If the Fermat spiral distribution is analyzed for a diameter of 48λ and 64 elements, three different angles provide solutions around them than can be considered as viable: 84°, 95° and 140°. Therefore, in this case the selection is addressed by manufacturing considerations like cable location, routing and how backing columns are distributed. In this sense, to reduce as much as possible the mechanical interaction between elements it is interesting to isolate each backing columns. These considerations point to the angle 140° as the more adequate for our purposes.

The simulated pulse-echo response of the aperture shows a lateral resolution of 1.2° and a dynamic range of 33 dB (Figure 3 Bottom).

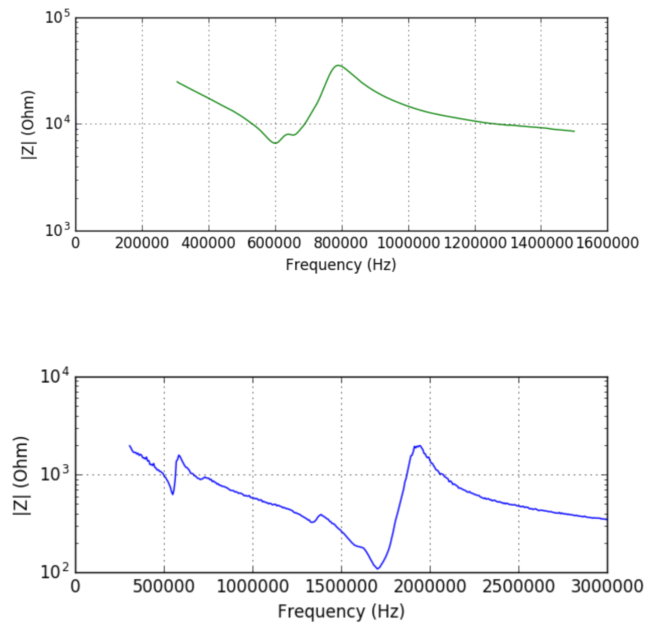

Fig. 2. Top: electrical impedance of 1.5×1.5 mm PZ27 (1MHz). Bottom: Electrical impedance of 1.5×1.5 mm 1-3 piezocomposite (851 material, Dice and Fill 65%, 1.5MHz)

IV. Manufacturing Process

Figures 4-7 describe the manufacturing process. The reduced cost of manufacturing allows to perform various prototypes and allows introduce small changes in order to refine the process. As it has been described the design model has been divided in two pieces. Figure 4 shows the first stage completed where the transducers have been allocated and fixed with Loctite™ 480. Figure 5 shows how cables are located and fixed near to the transducers with the electrical contact. Figure 6 shows the second stage just manufactured. It is a structure of 30 mm high. It includes in the inner part the backing cavities and in the outer, the slots to guide the cables from the transducer to where electronics would be integrated. Finally, Figure 7 shows the aperture with the two stages assembled, previous to be inserted into the shield and the insertion of the epoxy that constitutes the backing. After that, an elastomer is used to cover all the back generating a common dispersion space.

V. Experimental Results

Although there were developed several prototypes with different materials (see Figures from 4 to 7), the operative

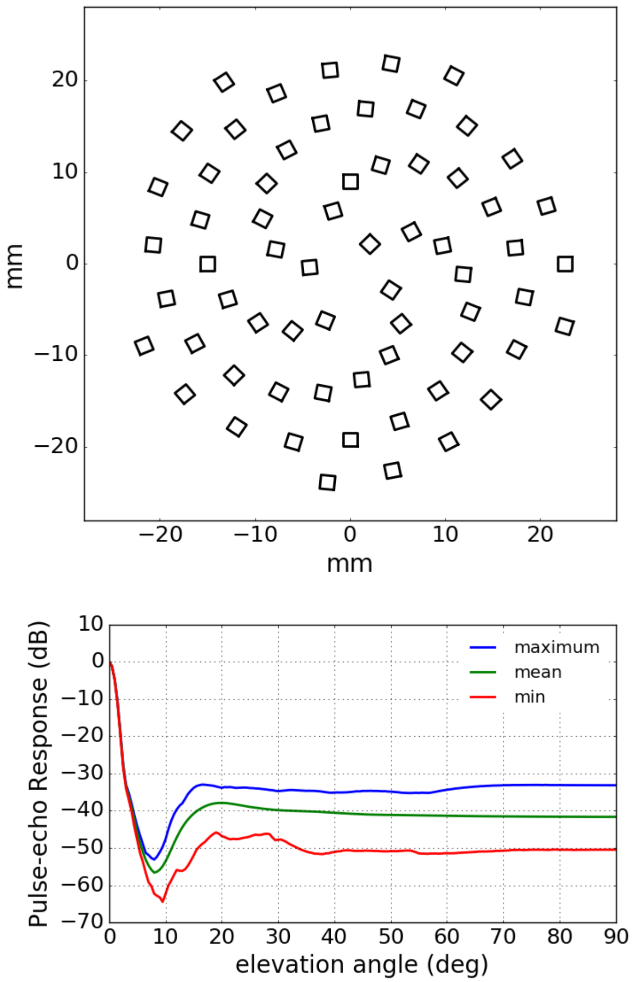

Fig. 3. Top: sparse array based on a Fermat spiral with a divergence angle of 140°. Bottom: lateral profile of the Point Spread Function computed in the semisphere ($\theta = 0^\circ : 90^\circ, \phi = 0^\circ : 360^\circ$). Blue line maximum values at each elevation angle. Green line mean values at each elevation angle. Red line min value at each elevation angle.

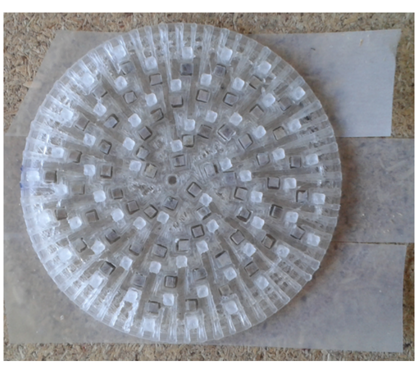

Fig. 4. Stage One. Each element has been inserted in its corresponding location. Allocation for the cable and its fixing points are included. Acetone has been used for cleaning and avoid shortcircuits.

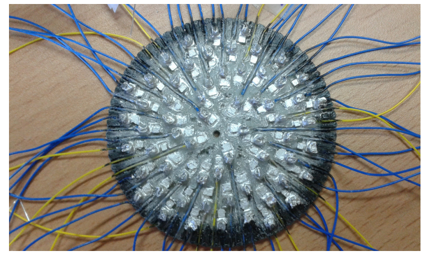

Fig. 5. Stage One. Each cable has been fixed in a column near its corresponding element. Conductivity between both element has been achieved by silver paint.

Fig. 6. Stage Two. Backing structure is distributed to cover each transducer. In the outer ways for the signals wires have been included. Central hole is incorporated to provide allocation for the ground wire.

prototype presented here is based on TPU and 1-3 piezocomposite. The electric conductivity between cables and transducer was achieved by silver paint. Preliminary test over this prototype have been carried. The electrical impedance has been measured and compared with previous pre-backing measures. In Figure 8 the corresponding impedance values for the sixth element are presented. The resonance frequency peaks have been smoothed and the lateral resonances have been reduced.

The mechanical behavior of the aperture has been evaluated with a vibrometer (Polytec PSV400). Figure 9 shows the displacement during the first cycle. Although all elements respond to the excitation, uniformity has not been achieved. This can be seen in Figure 10, where the temporal response of four elements (numbers: 6, 16, 34, 62) and its corresponding Power Spectral Density are presented. This responses have

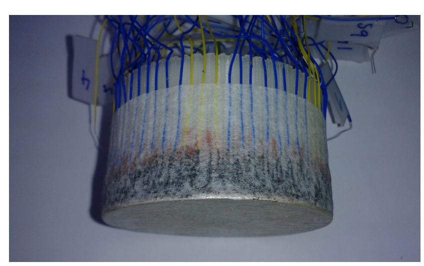

Fig. 7. Stage One and Stage Two assembled. Silver paint was used for the ground plane.

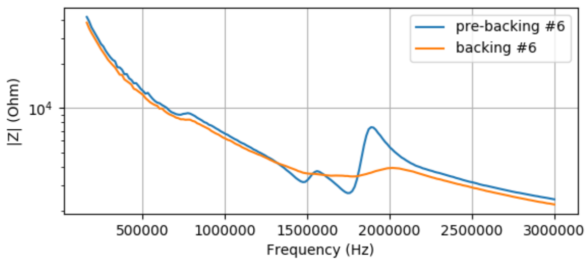

Fig. 8. Electrical Impedance of the element number 6. In blue previous to the backing insertion. In orange after the backing insertion.

been obtained as pulse-echo of a methacrylate planar surface. Central frequencies are kept around 1.6 MHz.

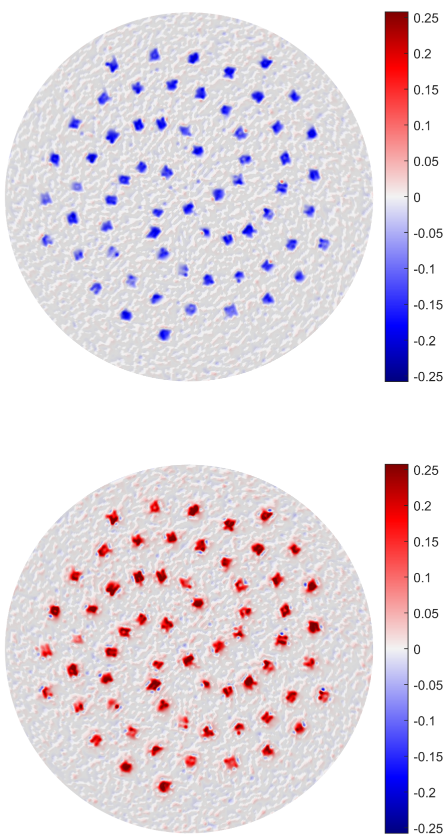

Fig. 9. Displacement of the ceramic piezocomposites when an excitation of 400 V is applied in one spike of $0.5\frac{\lambda}{c}$ wide. On top is presented the first semicycle. On bottom, the second.

VI. Conclusions

In this work a sparse array of 48λ diameter and 64 elements based on a Fermat spiral distribution has been designed and manufactured. In order to make it, a novel technique has been developed based on FDM. This technique has shown to be very versatile and cost effective. In this sense this technique

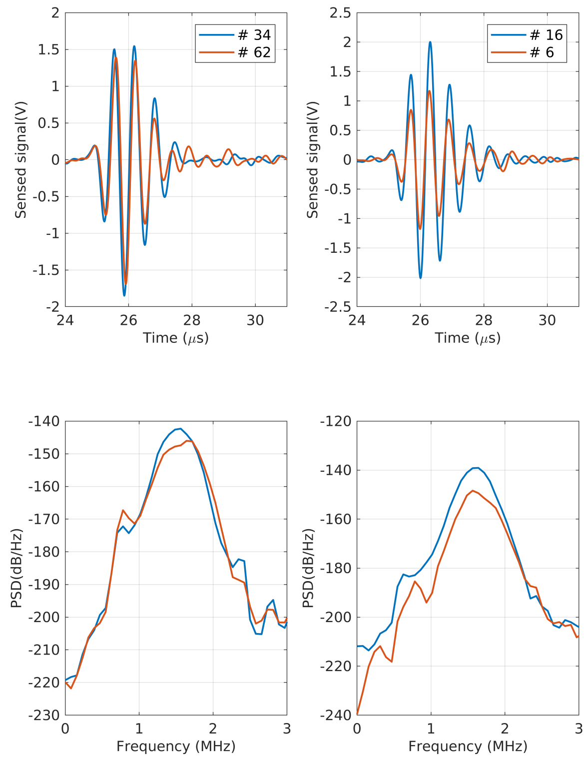

Fig. 10. Temporal response and Power Spectral Density of four elements of the aperture. Left: elements 34 and 62. Right: elements 6 and 16.

seems to be adequate for the development of risky proof-of-concept and can support an improvement of the arrays design tools.

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