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Development of innovative transducer designs for NDT applications: From 1-3 piezocomposite definition to 2D array probe manufacture

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Abstract

Phased array probes are now used in the industrial non destructive testing to replace single element transducers in targeted applications to enhance defect detectability and control speed. The complexity of the parts to be controlled and the environmental conditions in which the transducers are used require the development of specific ultrasound transducers and have triggered numerous R&D efforts in the recent years to improve the performances of NDT systems.
This presentation will describe innovative transducer designs for specific applications: development of dedicated 1-3 piezocomposite for phased arrays in high temperature configuration (above 100°C), extended range of shapes that can adapted to complex geometries, large range of frequencies (from 0.5MHz to 30MHz) to improve penetration and/or resolution and finally 2D arrays for volumetric imaging. All these applications will be presented from the ultrasound transducer manufacturer's perspective and challenges associated with the manufacture of such transducers will be discussed. We will focus on innovative 2D probes, including a 2MHz 128-element matrix array for nozzle welds inspection and a 5MHz 255-element annular-segmented phased array probe with dual concavity for titanium billets inspection.

Keywords: ultrasound, phased array, 2D array, nozzle weld, titanium

1. Introduction

The development of multi-element ultrasound probes has triggered numerous R&D efforts in the non-destructive applications in the recent years but these devices are commonly used in the medical imaging field for more than 20 years. The phased arrays have several advantages over single element configurations: the control is less dependent from the operator's expertise; the defect detectability and the speed of control are improved.
From the transducer manufacturer's perspective the phased arrays present several challenges to be overcome to achieve reliable configurations, among them the most noticeable are the small dimensions of the transducer layers and the large number of elements to be connected to the system with small pitch between elements.
The 1-3 piezocomposite material, which is the core material of the transducer, was developed more than twenty years ago [1] and is now widely used in the non-destructive testing. This article will emphasize the advantages of the piezocomposite for ultrasound transducer manufacture as well as some innovative designs developed for specific applications where the environmental conditions play a major role: we will therefore describe some piezocomposite configurations dedicated to high temperature applications before evaluating some innovative transducer configurations for high frequencies or 2D arrays for volumetric imaging.

2. Piezocomposite design

1-3 piezocomposite configuration, as described in the figure 1, has several advantages for the manufacture of ultrasound transducer. Its dual structure, with rods of piezoelectric ceramic embedded into a resin matrix, allows a large range of acoustical and mechanical properties as well as a good flexibility of the material as it is possible to modify the ceramic volume fraction in order to adjust the properties of the final material.

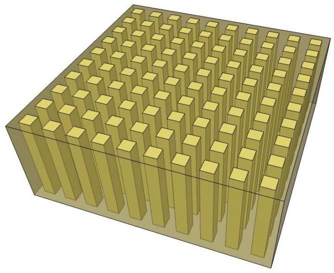


Figure 1: 1-3 piezocomposite description with ceramic plots (yellow) embedded into resin matrix (transparent)

We will describe here after the work performed on two specific configurations: high temperature and high frequency multi-element arrays.

2.1 High temperature piezocomposite

Environmental conditions are a key issue when defining the specifications of a transducer. Temperature of use is often neglected in the specifications and standard transducers – single element or phased arrays – are only guaranteed for temperatures between +10°C and +50°C in use (-20°C to +60°C in storage). This is due to the materials used in all steps of transducer manufacture: piezocomposite, matching layers, potting resins… For the development of transducers that can withstand to higher temperatures, properties of all transducer layers have to be carefully examined and specific integration techniques have to be developed. Present article describes piezocomposite to be used up to 120°C.

Different piezocomposite structures have been investigated to identify the main parameters for the design of high temperature materials as described in reference [2]. These structures include different piezoceramics (with different permittivities) and different filler materials (two types – F1 phenolic and F2 epoxy resin) as described in the table 1.

	C1	C2	C3	C4	C5
Ceramic type	highε1	lowε	high ε2	lowε	high ε2
Filler type	F1	F1	F1	F1	F2
Volume fraction	56%	66%	56%	56%	56%

Table 1: piezocomposite configuration details

For example, considering the piezocomposites C3 and C5 (same piezoceramic, different filler materials) it can be seen from the figure 2 that for these two configurations the properties that are very similar at room temperatures are quite different at higher temperatures where the lower thermal stability of the resin F2 degrades the piezoelectric performances of the piezocomposite at high temperatures.

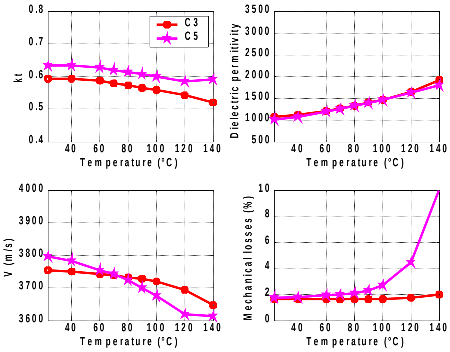


Figure 2: comparison of the properties of the piezocomposite C3 and C5 (coupling coefficient, dielectric constant, velocity and mechanical losses)

This study demonstrates that, for this temperature range, the filler material is the key material in the development of high temperature piezocomposite. We have therefore focused our research on the filler material to assess the best candidate for this type of applications. 5MHz 32-element phased array was developed as a result of this research [2].

2.2 High frequency piezocomposite

The manufacture of high frequency piezocomposite and high frequency ultrasound arrays is quite challenging due to the small dimensions of all transducer layers. At these frequencies the main issue is also related to the lateral modes that degrade the acoustical behaviour of the probe. This requires taking specific provisions in terms of piezocomposite manufacture as the kerf width has to be minimised to suppress these parasitic modes: as an example, for a 40MHz piezocomposite plate, kerf width should not exceed 8µm. The choice of the filler resin is also critical. In this case, to avoid lateral modes, a hard resin with high velocities is required.
As composite thickness is very low and ceramic plots very narrow in the piezocomposite, damages and crackings can occur during the piezocomposite manufacture. Low grain size ceramics are therefore needed for these applications as grain size shall be almost 10 times smaller than ceramic plots in the composite. As array elements have also very small pitch, high permittivity ceramic is also needed to match the electrical impedance between transducer and ultrasound system.

Several articles have already been presented on high frequency arrays ([3] and [4]). Current R&D efforts in high frequency piezocomposite allow the manufacture of 128-element 40MHz array (pitch 50µm, elevation 2mm) as described in [4] and typical time and frequency responses are reported in figure 3 (centre frequency: 38MHz; pulse length at -20dB = 86ns, measurements performed in water on pulse echo mode on a flat stainless steel target with pulser/receiver panametrics 5073pr).

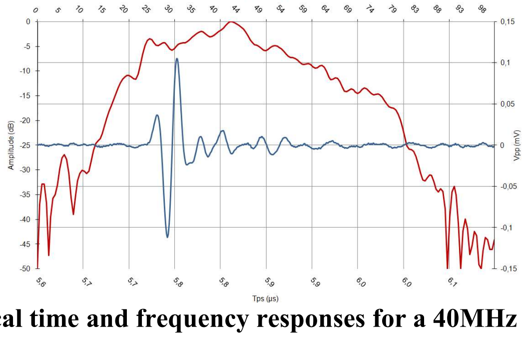
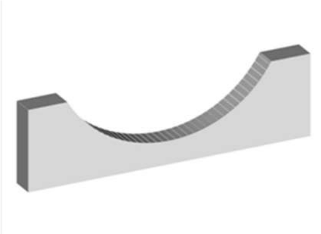


Figure 3: typical time and frequency responses for a 40MHz element array

3. 2D arrays and innovative designs

The previous chapter shows the advantages of the 1-3 piezocomposite configuration for different applications, due to the adjustable properties of this material as a function of the ceramic volume fraction.
Another advantage of the 1-3 piezocomposite is its flexibility: you can bend this material to achieve concave arrays or arrays with a transverse radius along the elevation as shown in figure 4. This allows also the manufacture of complex geometric shape (see paragraph 3.2).



(a)

(b)

Figure 4: (a) concave array configuration (b) array with transverse radius along the elevation

3.1. 2D arrays

Basic concept of 2D array is to have elements in both directions as described on the figure 5. To benefit from this configuration, elements have to be small in both directions to provide efficient beam control in all directions. This leads to some challenges for both transducer manufacturer (to develop the adequate technology to connect all the elements) and ultrasound system manufacturer (to be able to drive a high number of elements through appropriate electronics: as an example 64x64 elements = 4096 elements!).

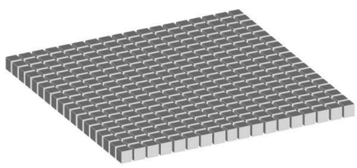


Figure 5 : 2D array configuration

We have already presented some 2D arrays configurations that overcome some of these issues (see [5] for medical imaging applications or [6] for non-destructive testing) and we would like to describe in this article two recent configurations to address specific applications.

3.2. 2D array for nozzle welds inspection

The probe described here after was manufactured in the frame of a European project "Nozzle Inspect" [7] funded by the European Commission. The objective of this project was to develop an automated robotic system including a phased array probe to assess and monitor the nozzle welds used in the nuclear power plants and mainly in the nuclear reactors. A complete system was developed in this project including probe, probe holder and robotic assembly that allows the probe to move around the nozzle and inspect the complete weld [8].

Several configurations were evaluated by some Partners of the project to assess the most suitable configuration ([9]), taking into account the manufacturing feasibility of the probe. Among these configurations we can describe (see figure 6):

- 1D array (figure 6a): standard phased array configuration ; only for comparison purposes as this configuration doesn't allow the deflection of the ultrasound beam in all directions
- 2D array (figure 6b): this configuration allows the deflection of the beam in all directions
- 2D annular segmented array (figure 6c): this is the most complex configuration that leads to differences in elementary areas.

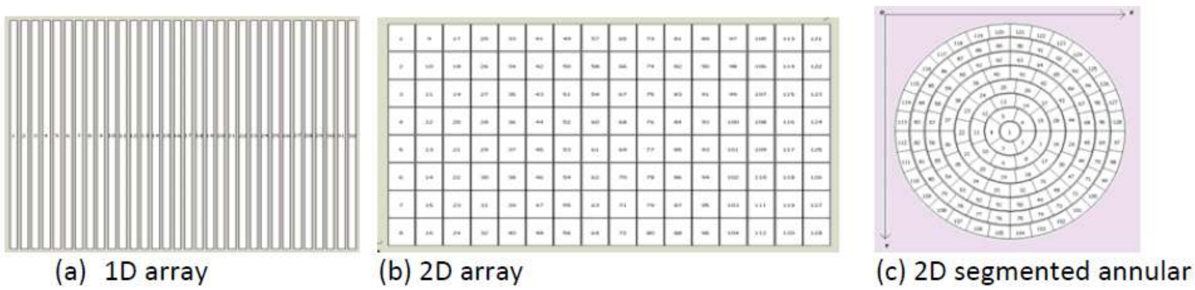
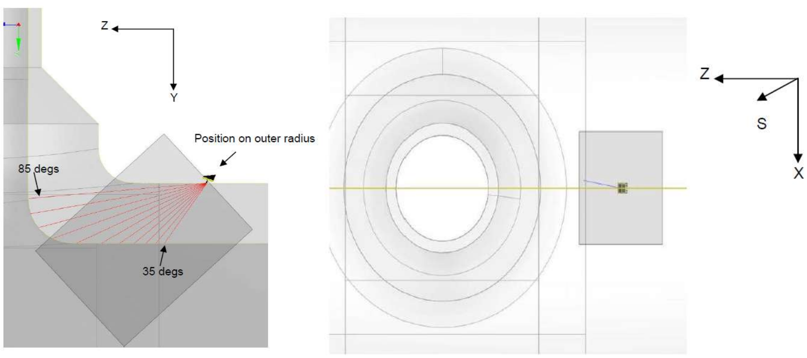


Figure 6: examples of phased array probe configurations evaluated during the design phase

The modelling was conducted by TWI Ltd, using CIVA software. It was performed on the YZ plane as defined in figure 7(a) for the sectorial scanning. The modelling was also performed in the plane that is perpendicular to YZ plane and at an angle of 40° with respect to the Y axis (this plane is called XS as described in the figure 7(b)).



(a) **(b)**

Figure7: (a) position of the transducer when used for sectorial scanning
(b) beam steered at 40° and skewed at 10°

The modelling studies demonstrate that a 2D array at 2MHz centre frequency with 128 rectangular elements in water is the most suitable configuration for this application. The resulting ultrasound beam presents some grating lobes but these are not detrimental for the considered control (figure 8).

For the different configurations the beam amplitude, focal area and focal depth were also modelled and confirmed the suitability of this 2D array configuration. It was demonstrated that the selected configuration gives the highest amplitude of ultrasonic beam when steering the beam at 40°, that the focal depths of -3dB and -6dB are the largest and that the focal zone is able to reach the bottom of the inspected component. The capability of this array on electronic beam skewing was also assessed and a maximum skewing angle of 20° was achieved.

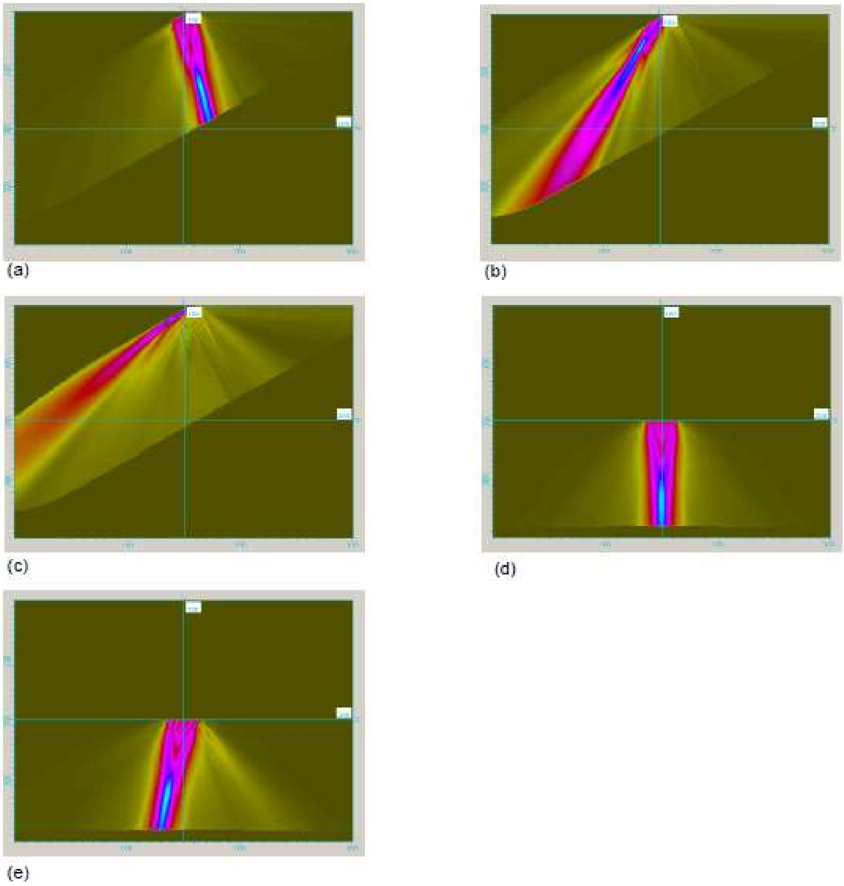


Figure 8: modelling of the beam profiles for the selected 2D array with the beam steering at (a) 40° in the YZ plane, (b) 65° in the YZ plane, (c) 85° in the YZ plane, (d) 40° in the YZ plane and the profile shown in the XS plane (e) 40° in the YZ plane and 10° in the XS plane and the profile shown in the XS plane

The manufacture of this type of transducer includes several steps:

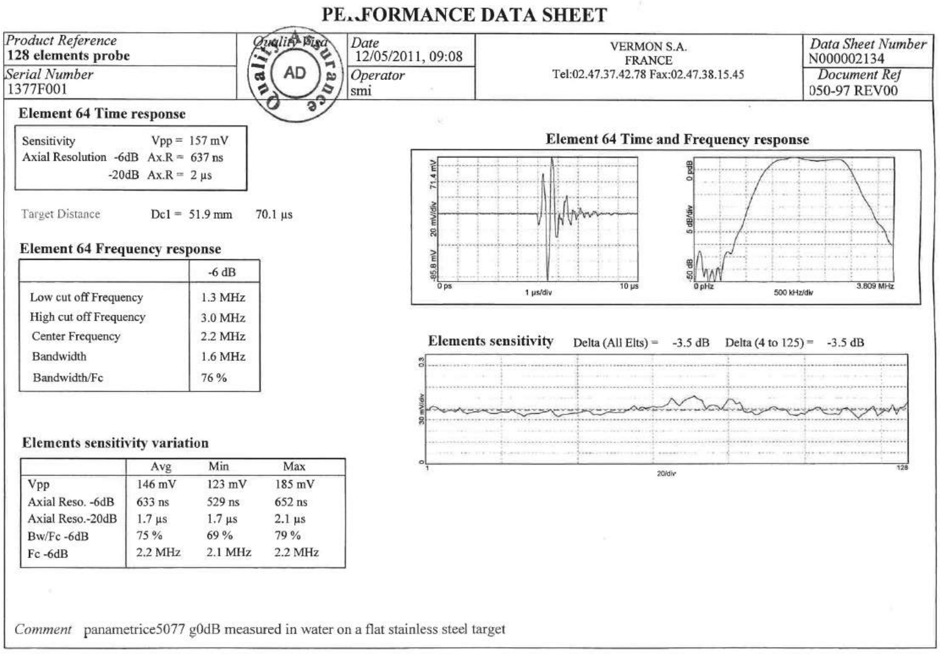
- Piezocomposite definition: a 1-3 piezocomposite adapted to the requested frequency and to the element dimensions was prepared with a ceramic volume fraction of 45%.
- Element patterning
- Assembly of the piezocomposite and the matching layers
- Soldering of the wires to connect all probe elements
- Backing molding
- Interconnection to micro-coaxial cables
- Integration into the housing and performances assessment.

The pictures 2 (a) and (b) show the manufactured probe.

(a) **(b)**

Pictures 2 (a) front face of the Nozzle Inspect probe and (b) complete probe

Electro-acoustical characterisation of the probe was conducted with a standard procedure: probe was placed in a water tank, in front of a stainless steel target and all elements were measured, in pulse echo mode with a Panametrics5077 pulser/receiver.



PE..FORMANCE DATA SHEET

Product Reference 128 elements probe	*Quality Visa*	*Date* 12/05/2011, 09:08	VERMON S.A. FRANCE Tel:02.47.37.42.78 Fax:02.47.38.15.45	*Data Sheet Number* N000002134
Serial Number 1377F001		*Operator* smi		*Document Ref* 050-97 REV00

Element 64 Time response

Sensitivity Vpp = 157 mV
Axial Resolution -6dB Ax.R = 637 ns
-20dB Ax.R = 2 µs

Target Distance Dc1 = 51.9 mm 70.1 µs

Element 64 Frequency response

	-6 dB
Low cut off Frequency	1.3 MHz
High cut off Frequency	3.0 MHz
Center Frequency	2.2 MHz
Bandwidth	1.6 MHz
Bandwidth/Fc	76 %

Elements sensitivity variation

	Avg	Min	Max
Vpp	146 mV	123 mV	185 mV
Axial Reso. -6dB	633 ns	529 ns	652 ns
Axial Reso.-20dB	1.7 µs	1.7 µs	2.1 µs
Bw/Fc -6dB	75 %	69 %	79 %
Fc -6dB	2.2 MHz	2.1 MHz	2.2 MHz

Element 64 Time and Frequency response

Elements sensitivity Delta (All Elts) = -3.5 dB Delta (4 to 125) = -3.5 dB

Comment panametrice5077 g0dB measured in water on a flat stainless steel target

Figure 9: homogeneity performances of the Nozzle Inspect probe

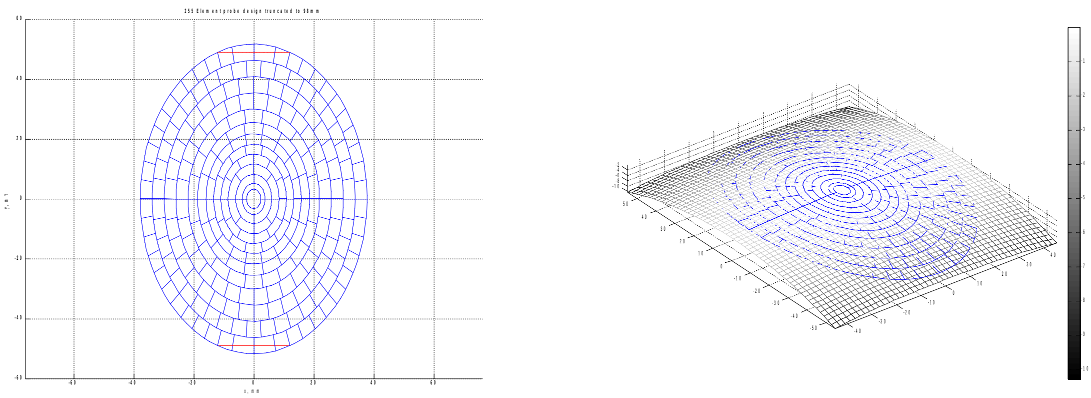
General sensitivity homogeneity of the probe (see figure 9) is at 3.5dB. A high bandwidth is also achieved (75%) and a centre frequency of 2.2MHz was measured with a pulse length (@-20dB) at 1700ns (average values).

3.3. Annular-segmented phased array probe with dual concavity for titanium billets inspection

The manufacturing process of titanium billets can produce sub-surface defects that are particularly difficult to detect during the early stages of production and the aerospace industry demands higher quality standards of Titanium billet products to ensure safety. To meet this challenge, a new and novel automated quality inspection system was developed in the frame of a European-funded project QualiTi [10] that combines multicoil eddy current inspection (surface and subsurface defects) with phased array ultrasonic inspection (deep defect inspection).

Design of the ultrasound probe is described in reference [11]. The probe is a 2D sectorial annular curved probe with a dual concavity shape (figures 10). It has an elliptic shape (long axis 98mm and short axis 78mm). The probe includes 255 elements distributed on 1 central element, 12 rings with elements of same area on each ring (the first ring has 2 elements, the last one 48 elements with 8 truncated elements)

The probe and probe shape have been designed to deliver a 2.5 mm diameter beam spot at all inspection depths from just beyond the blind zone (5 mm) to half an inch past the centre of the 10” billet (139 mm from the surface).



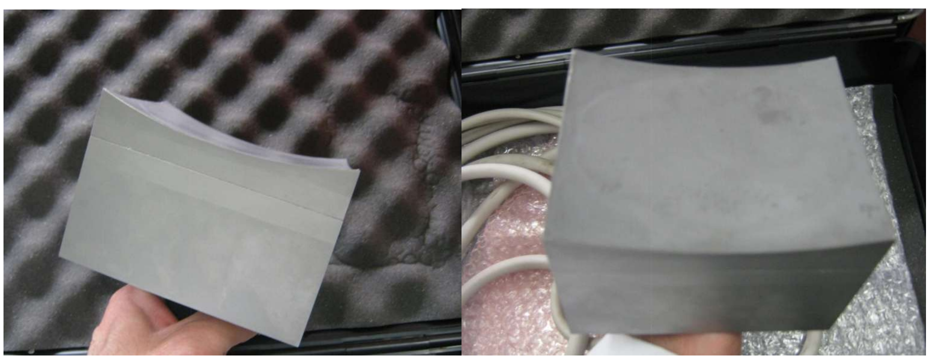
(a) **(b)**

Figure 10: (a) probe element distribution (b) probe complex shape

The proposed probe design is very innovative and includes several challenges that need to be overcome to complete probe manufacture:

- First challenge is related to the **large dimensions** of the probe (98mmx78mm): each transducer requires the manufacture of one large piezocomposite plate.
- The **large number of elements** (255) is also challenging.
- The **positioning of the elements** and the correct addressing is also critical for the tests. A specific calibration block was prepared for the characterization of the probe to verify this addressing.
- The **variation in transducer element areas** is also an issue for the performances of the probe. This leads to different electrical impedance for the elements along the probe as no individual impedance matching was performed for this prototype. It was nevertheless decided to keep the elementary area identical for all elements of one ring.
- The **complex shape** of the probe requires the development of specific toolings to achieve the appropriate shape and to maintain it all along the manufacturing process.

Manufacturing process for this probe is very similar to the process described before in paragraph 3.2 with specific provisions to ensure the respect of the designed shape for the probe. The pictures 3 show the complete probe.



Pictures 3: views of the complete probe

It is not possible to perform the homogeneity performances for the whole probe as different element areas lead to different sensitivity levels. We measured the capacitance of all elements as reported in figure 11 (measurements are in good agreement with the theoretical modelling). The drop in the capacitance measurement for the 12^{th} and last ring is related to the presence on this ring of truncated elements.

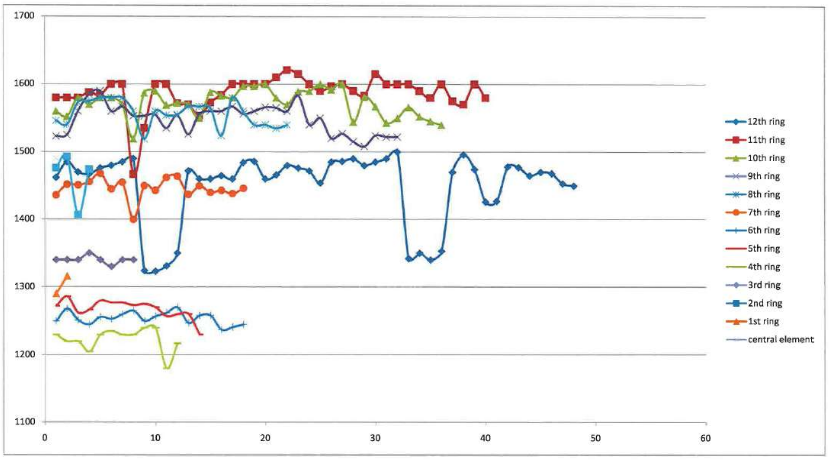
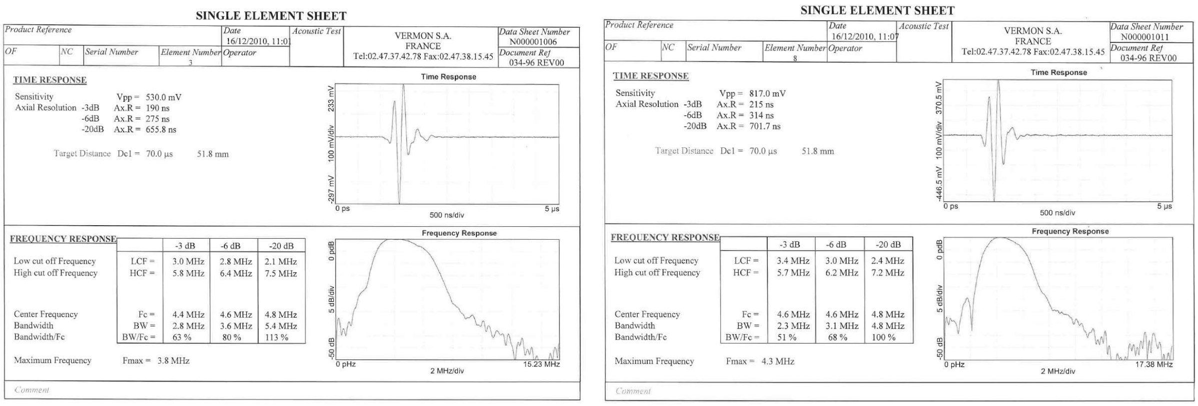


Figure 11: measurements of element capacitance along the array as a function of ring position

Finally electro-acoustical characterisation of the probe was performed and figure 12 shows the performances of some elements along several rings.



Figures 14: time and frequency responses for elements 3 (first ring) and 8 (second ring)

The probe was further evaluated in the frame of the project and it was demonstrated that it performs well on titanium billets inspection with targeted defect characterisation level.

4. Conclusion

This article reviews some key factors in the design of 1-3 piezocomposite configurations. Due to the possibility to modify the different parameters of this material (selection of the piezo-ceramic and of the filler resin, ceramic volume fraction) it is possible to adjust the final properties of the material to different application requirements such as those related to high temperature or high frequency behaviour.

Phased arrays for non-destructive testing have been developed extensively these last ten years and have demonstrated their added value as compared to single element configurations in the control reliability and speed. Some innovative designs have been described in this article with 2D array configurations for specific applications (nozzle welds inspection and titanium billets inspection). These designs represent interesting challenges for the ultrasound probe manufacturer to develop dedicated processes to match the requirements of these applications. These designs also show that the increase of phased arrays use and their improvements will be driven by the end users and by the applications. End users should not limit their imagination and should suggest new designs to transducer manufacturers!

Acknowledgments

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