Optimization of Phased-Array Transducers for Ultrasonic Inspection in Composite Materials Using Sliding Probes

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Abstract
The increasing use in the industries of composite materials implies finding a suitable way for testing and evaluating them. Non-destructive testing by ultrasounds is an appropriate method to detect defects in this type of materials, however, because of their structure it is required to find the most applicable and accurate process for detecting flaws and anomalies in them.

For conventional ultrasound testing, single-element probes are used to generate an ultrasonic signal that is transmitted into the material to inspect it. However, when inspections are done on composite materials, phased array probes (PA) are used in order to detect component failures and thereby determine their quality.

Such transducers, in contrast with conventional pulse echo ones, use multi-element probes, so that each element can be pulsed independently and therefore transmit and receive signals at different times. In addition, PA probes can be designed in a wide variety of geometries, allowing them to be customized for particular applications. These transducers come in a wide variety of sizes, frequencies, and case styles, but most of them have a common internal structure. Phased Array Ultrasound techniques offer several benefits including better detection, faster scanning, and traceable results.

The use of ultrasonic transducers involves the need of using a coupling element that allows the introduction of the ultrasonic beam on the piece to be inspected. Water is the most widely coupling medium used but has many disadvantages in-service inspections. A dry-coupling method is therefore desired for fast and cost efficient inspections. In this way, a few years ago rubber materials appeared with ultrasonic properties similar to water, which were incorporated into the probes for inspection of CFRP in two formats: “Sliding probes” or “Wheel probes”. The use of dry coupling for applying ultrasonic testing is an increasingly important practice mainly for the inspection of non-uniform surfaces.

The objective of this study is to optimize this type of ultrasonic inspection transducers PA regarding ultrasonic parameters inherent to the probe in relation with the specifications and laws of ultrasonic propagation, the constructive aspects as well as those more general aspects which affect the productivity in the inspections such as coupling material with better signal / noise relation and higher wear resistance than polybutadiene polymers that nowadays exist in the market.

Keywords: Ultrasonic, Phased array, Dry coupling, Composite materials inspection, sliding probes.

1. Introduction
In its simplest form, one can think of a phased array probe as a series of individual elements in one package. While the elements in reality are much smaller than conventional transducers, these elements can be pulsed as a group so as to generate directionally controllable wave fronts. This 'Electronic Beam Forming' allows multiple inspection zones to be programmed and analyzed at very high rates of speed from a single position transducer.

The purpose of this study is to optimize the phased array transducers, regarding coupling and ultrasonic behaviour.
In the first part of this work, coupling materials based on polybutadiene polymers already available in the market are been compared with a new formulation obtained by Tecnitest. Likewise in a second part an analysis of design parameters for sliding probes PA used in inspection by Pulse Echo (PE) is performed in order to optimize them from the point of view of the ultrasonic behavior as well as enabling easy use in inspection activities.

2. Phased array transducers

The responses produced by phased array transducers, like those from any other ultrasonic transducers for NDT, will be related both to transducer design parameters like frequency, size, and mechanical damping, and to the parameters of the excitation pulse that is used to drive it.

Phased array transducers are functionally categorized according to the following basic parameters: **type, frequency, number of elements, and size of elements**

- **Type**: Most phased array transducers are angle beam type, designed for use with either a plastic wedge or a straight plastic shoe (zero degree wedge) or delay line.

- **Frequency**: The test frequency has a significant effect on near field length and beam spreading. In practice, higher frequencies can provide better signal to noise ratio than lower frequencies. At the same time, penetration in any test material will decrease with frequency because of increasing material attenuation as frequency goes up. Commonly, industrial phased array probes are offered with frequencies between 1MHz and 15MHz.

- **Number of elements**: Phased array transducers most commonly have 16 to 128 elements, with some having as many as 256. A larger number of elements increases focusing and steering capability, and can increase area coverage as well. Each of these elements is individually pulsed to create the wavefront of interest. Hence the dimension across these elements is often referred to as the active or steering direction.

- **Size of elements**: The minimum practical element size is typically around 0.2mm. As the size of individual elements in an array decreases, its beam steering capability increases. However if the element size is less than one wavelength, strong unwanted side lobes will occur.

- **Pitch and aperture**: Pitch is the distance between individual elements, aperture is the effective size of a pulsing element that is usually comprised of a group of individual elements that are pulsed simultaneously (virtual aperture). To optimize steering range, pitch must be small. For optimum sensitivity, minimum unwanted beam spreading, and strong focusing, the aperture must be large.

Whenever waves originating from two or more sources interact with each other, there will be phasing effects leading to an increase or decrease in wave energy at the point of combination.

The programmed pulsing sequence selected launches a number of individual wave fronts in the test material. These wave fronts in turn combine constructively and destructively into a single primary wave front that travels through the test material and reflects off cracks, discontinuities, back walls, and other material boundaries like any conventional ultrasonic wave.
The beam can be dynamically steered through various angles, focal distances, and focal spot sizes in such a way that a single probe assembly is capable of examining the test material across a range of different perspectives.

This beam steering happens very quickly, so that a scan from multiple angles or with multiple focal depths can be performed in a small fraction of a second.

2.1. Beam shaping

The response of any ultrasonic test system is a combination of factors: the transducer used, the type of instrument used and its settings, and the acoustic properties of the test material.

The responses produced by phased array transducers, like those from any other ultrasonic transducers for NDT, will be related both to transducer design parameters like frequency, size, and mechanical damping, and to the parameters of the excitation pulse that is used to drive it.

The key concepts for a general understanding phased array beam can be summarized as follows: A group of elements is fired with a programmed focal law. This builds the desired transducer aperture and beam characteristics.

<table>
<thead>
<tr>
<th>Decreasing pitch and elements width with number of elements constant</th>
<th>Increases beam steering capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increasing pitch or frequency</td>
<td>Creates unwanted grating lobes</td>
</tr>
<tr>
<td>Increasing element width</td>
<td>Creates side lobes (as in conventional UT), reduces beam steering</td>
</tr>
<tr>
<td>Increasing active aperture by using many small elements with small pitch</td>
<td>Increases focusing factor (sharpness of beam)</td>
</tr>
</tbody>
</table>

2.2. Beam steering

The essence of phased array testing is an ultrasonic beam whose direction (refracted angle) and focus can be steered electronically by varying the excitation delay of individual elements or groups of elements. This beam steering permits multiple angles and/or multiple point inspection from a single probe and a single probe position.

Ultrasonic beam characteristics are defined by many factors. In addition to element dimension, frequency and damping that govern conventional single element performance, phased array transducers behaviour is affected by how smaller individual elements are positioned, sized and grouped to create an effective aperture equivalent to its conventional counterpart.

For phased array transducers N elements are grouped together to form the effective aperture for which beam spread can be approximated by conventional transducer models.
2.3. Grating lobes and side lobes

Another phenomenon associated with phased array probes is the generation of unwanted grating lobes or side lobes, two closely related phenomena caused by sound energy that spreads out from the transducer at angles other than the primary path.

The amplitude of grating lobes is significantly affected by pitch size, the number of elements, frequency, and bandwidth.

Grating lobes will occur whenever the size of individual elements in an array is equal to or greater than the wavelength, and there will be no grating lobes when element size is smaller than half a wavelength. (For element sizes between one-half and one wavelength, the generation of grating lobes will depend on the steering angle).

2.4. Focusing with phased array probes

The beam diameter at any distance from the transducer can be calculated. In the case of a square or rectangular phased array transducer, beam spreading in the passive plane will be similar to that of an unfocused transducer. In the steered or active plane, the beam can be electronically focused to converge acoustic energy at a desired depth.

3. New material for dry coupling

For some years it has been used dry coupling for inspections using Ultrasonic Techniques (UT). The areas where the dry coupling has been used are: Nodularity Testing, Roller probe (both single crystal and multi-crystal applications), Sliding probes and Spot Weld Inspection. The aim of this study has been to develop a new rubber that allows dry coupling in the above applications with even better than existing materials based on polybutadiene (hereinafter material type ’R’ properties).

Taking as reference the type 'R' material, their properties were analyzed and produced a similar material in 2 forms, Sample A and Sample B.

<table>
<thead>
<tr>
<th>Description</th>
<th>Density</th>
<th>Sample A</th>
<th>Sample B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution polymerized 96% CIS</td>
<td>0.91</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>Carbon Black; N907</td>
<td>1.8</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Process oil; paraffinic</td>
<td>0.906</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Zinc Oxide</td>
<td>5.6</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Activator</td>
<td>0.85</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Accelerator A</td>
<td>1.28</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Accelerator B</td>
<td>1.18</td>
<td>1.8</td>
<td>1.8</td>
</tr>
<tr>
<td>Sulphur, soluble, oil coated</td>
<td>2.04</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>HIGH CIS BR (&gt;97%)</td>
<td>0.91</td>
<td>-</td>
<td>100</td>
</tr>
</tbody>
</table>

The two samples were tested for acoustic attenuation. Results in the sample 'A' were very encouraging, but not for the 'B' which had an attenuation too high.
A comparison between 'A' material and 'R' material was performed. For this purpose was used a Sonatest Masterscan 380 equipment and three different transducers: SP496 (10 MHz), RDT 2550 (5 MHz) and IMR 501 (1 MHz)

The results were as follows:

<table>
<thead>
<tr>
<th>Transducer</th>
<th>First Echo Signal 'R' Rubber</th>
<th>First Echo Signal 'A' Rubber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Screen Height</td>
<td>Gain (dB)</td>
</tr>
<tr>
<td>SP496 (10MHz)</td>
<td>80%</td>
<td>61</td>
</tr>
<tr>
<td>RDT2550 (5MHz)</td>
<td>80%</td>
<td>29</td>
</tr>
<tr>
<td>IMR 501 (1MHz)</td>
<td>80%</td>
<td>18.5</td>
</tr>
</tbody>
</table>

- For type 'A' material an average velocity of 1507m/s was obtained. This was one of the goals wanted, to achieve a material with a velocity much the same as the water (~1500m/s)
- For material 'A' signal/noise ratio was excellent and tests performed on known defects had good results.
- Also, wear resistance tests showed that this material works well for this purpose

The difference between the gain levels for the materials could be explained by the thickness of the material. The 'R' material was 10mm thick whereas the 'A' one was only 6.35mm thick. Similarly, the gain levels at the lower frequency that are the same could be due to differences in the size of the sample.

The 'A' delay material should be considered as a suitable replacement for applications, such as nodularity, sliding probe and roller probe, where the stiffer material gives suitable durability.

However, it was considered that it may be a little hard for some applications where the rubber has to conform to the profile of the surface.

4. Phased array probe selection summary

As indicated previously, designing phased array probes is always a compromise between selecting the proper pitch, element width and aperture.

Using a high number of small elements to increase steering, reduce side lobes and provide focusing but can be limited by cost of manufacturing and instrument complexity.

Most standard instruments will support apertures of up to 16 elements. Separating elements greater distances may seem the easy way to gaining aperture size, but this creates unwanted grating lobes.

Actual transducer selection will ultimately be driven by the end application needs. In some cases multi-angle steering will be required over small metal paths so large aperture sizes are not needed or desired.
In other cases the application may be to cover large areas for laminar defects will require large apertures and linear scan format with multiple grouped elements where steering is not required at all.

5. Selecting parameters of PA: Analysis

The dimensional parameters of a phased array are customarily defined as follows

\[ \begin{align*}
N &= \text{total number of elements in the array} \\
A &= \text{total aperture in steering or active direction} \\
H &= \text{element height or elevation. Since this dimension is fixed, it is often referred to as the passive plane.} \\
p &= \text{pitch, or center-to-center distance between to successive elements} \\
e &= \text{width of an individual element.} \\
g &= \text{spacing between elements}
\end{align*} \]

5.1. Frequency and sensitivity on inspection

In a test, the frequency employed determines the ability to penetrate the material, so that the ultrasound beam is not excessively damped, in order to echoes corresponding to defects are clearly identifiable in relation to noise.

The sensitivity for detecting defects of a certain size is of the order of the ultrasonic wavelength in the material. Known ultrasonic propagation velocity in a material can determine the wavelength \((\lambda)\) depending on the frequency used, and therefore the sensitivity.

Inside the aeronautical sector, in a pulse-echo inspection mode, the frequency of 5 MHz is satisfactory to meet inspection requirements most of the structures made of CFRP (Carbon Fiber reinforced Plastics). Usually, the laminates have a thickness of less than 30 mm, with a defect size of 6mm x 6mm which means that it is necessary to detect reliably defects of 3x3mm. The wavelength of the ultrasonic beam is approximately 0.63mm so with a frequency of 5 MHz, it implies an adequate intrinsic sensitivity.

In sandwich structures, frequencies used are generally less than 5MHz. Frequencies of 1MHz or 2MHz are common in Through Transmission (TT).

Although wavelength values indicate the minimum absolute values of sensitivity provided by the assay, possible variations in the ultrasonic propagation velocity as well as other factors regard in a robust process in terms of an industrial trial, for a given frequency, it is possible to detect defects on the order of over 4 times the corresponding wavelength. For example if Frequency= 5MHz defect size 3x3 mm could be detected.
5.2. Pitch/spacing between elements, width of an individual element and aperture

At the time of making the choice two generic aspects must be considered.

- regarding the pitch, dimensions of the array elements, and total number of elements, already existing combinations must be considered.
- active area offered by the industrial equipment PA are equally limited.

The choice of element height or elevation is a key aspect. It should have a value equal to or greater than the minimum default size that is necessary to detect according to the test frequency so that the defect can be completely 'focused' by the beam in the corresponding spatial dimension.

Regarding to the number of elements of the total aperture, these must approach the value of elevation in order to have an active area which is nearly the square dimension. So, the array could be assimilated to a monocrystal probe with the same square surface.

Given the above considerations, a selection of linear probes was performed for inspection of CFRP materials in the aerospace manufacturing industry.

For this purpose, probes have been selected between 32 and 128 elements, representing a length of the array from 26mm to 128mm.

Thus, it has been covered an adequate range of probes that could be adapted to the dimensions of the pieces, making easier inspections and improving productivity

5.3. Thickness of the delay

In order to calculate the delay of the coupling, two important aspects must be taken into account, the size of the near field and the presence of second or subsequent rebounds in the A-scan, because both of them will have a fundamental importance.

For a PA transducer, the length of the near field to the beam can be calculated such as:

\[ N = \frac{K \cdot A^2}{4 \cdot \lambda} \]

if \( H < A \) (As in monocrystal)

Where K is the aspect ratio, based on the ratio between the short and long dimensions of the element or aperture:

<table>
<thead>
<tr>
<th>Ratio short/long</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1.37 (square element)</td>
</tr>
<tr>
<td>0.9</td>
<td>1.25</td>
</tr>
<tr>
<td>0.8</td>
<td>1.15</td>
</tr>
<tr>
<td>0.7</td>
<td>1.09</td>
</tr>
<tr>
<td>0.6</td>
<td>1.04</td>
</tr>
<tr>
<td>0.5</td>
<td>1.01</td>
</tr>
<tr>
<td>0.4</td>
<td>1.00</td>
</tr>
<tr>
<td>0.3 and below</td>
<td>0.99</td>
</tr>
</tbody>
</table>
In the case of circular elements, K is not used and the diameter of the element (D) is used instead of the length term:

\[
N = \frac{\left(A^2 + H^2\right)}{2\pi \lambda} \left(0.78 - \frac{0.27 \cdot A}{H}\right) \quad \text{if } H > A \text{ (according to [2])}
\]

In this work, the value of N has been calculated according to the previous expressions. In addition, a water column (or rubber delay with equivalent ultrasonic properties, as in our case) is also required, of which length allows to neutralize a 70% of N (in water) before entering into the material.

Let us consider \( t_1 \) delay thickness and \( t_2 \) material thickness. In order to avoid that the second bounce on the interface (delay-material) arrives before the background echo in the pieces test and confused with internal echoes it is necessary that:

\[ t_1 > \frac{t_2}{2} \]

If \( t_2 = t_1 \) both echoes will coincide because in this case the velocity of the ultrasonic beam in the delay is half that in the material.

Therefore, in order to separate away these two echoes avoiding ghost echoes, it seems reasonable to set the following relationship between delay thickness and material thickness:

\[ t_1 > t_2 \]

Therefore it is necessary that simultaneously:

- \( t_1 \) is greater than material thickness
- \( t_1 \) is greater than or equal to 70% of the near field of the transducer in the water

In the cases analyzed, it was seen that the requirement for near field imposes values to the delay thickness higher than the requirement in order to avoid the occurrence of ghost echoes. Clearly as far as \( t_1 \gg t_2 \), better.

### 5.4. Beam spread angle and side lobes

From near field was calculated in all cases the beam spread angle.

\[ \alpha = \arcsin \left(0.514 \cdot \frac{\lambda}{A}\right) \]

The values obtained were less than 3 degrees, indicating that it is nearly a straight beam.

Regarding the presence of side lobes, the requirement \( e \) (single width of an element) \(<\lambda/2\), must be satisfied to ensure that the side lobes don't appear, but in a number of cases \( e<\lambda/2 \) is not met, however, is not a problem because:

- the corresponding beams remain in the delay
- laminate structure does not favour propagation of these beams.
5.5. Transducer design

The values obtained in our particular cases have been.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity in water (mm/s)</td>
<td>1.5</td>
</tr>
<tr>
<td>Velocity in CFRP (mm/s)</td>
<td>3.15</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&gt;60%</td>
</tr>
<tr>
<td>Sensitivity Homogeneity</td>
<td>±3dB</td>
</tr>
<tr>
<td>Nº elements</td>
<td>32 32 64 64 128</td>
</tr>
<tr>
<td>p (mm)</td>
<td>0.8 1 0.8 1 1</td>
</tr>
<tr>
<td>Length of the array (mm)</td>
<td>25.6 32 51.2 64 128</td>
</tr>
<tr>
<td>g (mm)</td>
<td>0.1</td>
</tr>
<tr>
<td>e (mm) = p - g</td>
<td>0.7 0.9 0.7 0.9 0.9</td>
</tr>
<tr>
<td>H (mm)</td>
<td>6.4</td>
</tr>
<tr>
<td>Active aperture (nº elements)</td>
<td>8</td>
</tr>
<tr>
<td>A (mm)</td>
<td>6.3 7.9 6.3 7.9 7.9</td>
</tr>
<tr>
<td>A/H or H/A (short dim/ long dim)</td>
<td>0.984 0.810 0.984 0.810 0.810</td>
</tr>
<tr>
<td>N (Water) (mm), ( if H&lt;A)</td>
<td>n/a 59.81 n/a 59.81 59.81</td>
</tr>
<tr>
<td>N (Water) ( if H&gt;A)</td>
<td>44 n/a 44 n/a n/a</td>
</tr>
<tr>
<td>Beam Spread (Degrees)</td>
<td>2.95 2.35 2.95 2.35 2.35</td>
</tr>
<tr>
<td>t_{min} [4] (\geq 70%)N (Water)</td>
<td>30.80 41.87 30.80 41.87 41.87</td>
</tr>
<tr>
<td>t_{1}&gt;t_{2}/2 (\Rightarrow) t_{1}=t_{2}</td>
<td>t_{2}&lt;30</td>
</tr>
<tr>
<td>t_{1}, Rubber delay thickness (mm)</td>
<td>31 42 31 42 42</td>
</tr>
</tbody>
</table>

At the same time a compromise between near field calculated and attenuation in the delay is necessary according to the frequency employed.

After selecting the inherent ultrasonic parameters of transducer PA, an important aspect to consider is the design of the constructive aspects surrounding the same probe and delay

- The rubber delay should have a small convexity on its underside to be better adapted to the surface.
- The casing must prevent lateral bulging in the delay
- The transversal axis of the probe should be kept parallel to the piece. The ultrasonic beam has to be perpendicular to the work-piece surface at each point.
- Also have to be considered those aspects affecting productivity improvement such as:
  - different widths for the different dimensions of the components,
  - location encoders that can be installed in two positions to 90 degrees
  - Cable long enough, to allow inspection of a single pass without having to move equipment PA
  - The casing is not too wide to avoid dead zones
  - The set can be used easily and ergonomically
The probe obtained, which satisfies all these indications is shown in the following figure

6. Conclusions

Throughout this paper we have presented a new material for dry coupling, based on already existing materials. In addition, we have made a selection of parameters to be used in inspections by Pulse-Echo with Phased-Array transducers. Finally a design of probes in order to improve testing productivity has been developed.

Acknowledgments

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References

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