8th European Congress on Non Destructive testing
June 17-21, 2002 - Barcelona – Spain

Phased Array technology
Concepts, probes and applications

Jérôme Poguet, Imasonic - France
Andres Garcia, Tecnatom – Spain
Jesus Vazquez, Tecnatom – Spain
Jerome Marguet , Imasonic - France
Fabrice Pichonnat, Imasonic - France

Abstract

Over the last few years, piezocomposite materials have enabled a new ultrasound probe technology to be developed for the Non-Destructive Testing of materials: Phased Array probes.
These probes, made up of a large number of simple probes organized in linear, annular, circular or matrix arrays, allow electronic scanning, focusing and deflection to be carried out. These different concepts will be presented, as well as their associated benefits in terms of performance, flexibility, speed and feasibility of certain inspections.
Different applications that have implemented this technology will also be presented, with details about the particular probes used. Through these applications, the benefits of phased array technology for many fields will be highlighted, including the nuclear, aeronautical and in-line testing industries.

Introduction

A certain number of industries requiring advanced means of Non-Destructive Testing, such as the nuclear, aeronautic or in-line testing industries, constantly seek improvements in the performance of their inspection and monitoring systems.
The most common requests concern an increase in productivity, reduction in the size of untested areas and improvements in detection and sizing performance. For the nuclear industry, it is also a major stake to reduce inspection times, dose and costs.
For the last 10 years, Imasonic has responded to these needs by designing and developing solutions based on Phased Array technology.
In the meantime, Tecnatom developed new solutions based on this technology for the nuclear industry, notably for CRD inspection, nozzle inspection or turbine blade inspection

The Phased Array concept

The Phased Array concept is based on the use of transducers made up of individual elements that can each be independently driven. These probes are connected to specially-adapted drive units enabling independent, simultaneous emission and reception along each channel. These units should also be able to effect, during both emission and reception, the different electronic time delays for each channel.
For some applications implementing electronic scanning, not all the elements of the probe are used simultaneously. In this case, the drive unit uses dynamic multiplexing to distribute the active elements among the elements of the transducer.

Electronic scanning

Electronic scanning, illustrated in figure 1, consists of moving a beam in space by activating different active apertures in turn, each one made up of several elements of a phased array probe.
It allows a mechanical scanning axis to be replaced electronically.
In general, this concept is used for in-line testing of plates, bars or tubes, and can also be used for inspecting welds.

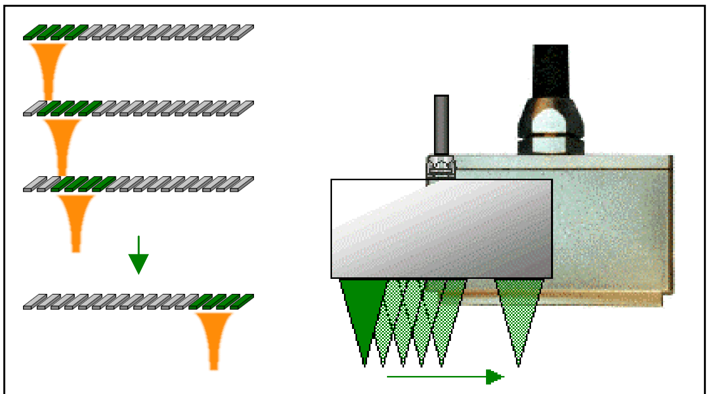


Figure 1 : Diagrammatic view of electronic scanning: groups of elements are successively activated to move the beam along the transducer

Electronic focusing

Electronic focusing, shown in figure 2, is based on the use of electronic delays applied during emission and reception along each of the channels of the probe. These delays have an effect similar to that of a focusing lens and enables focusing to different depths.
Electronic focusing allows only one phased array probe to be used where several single-element probes with different focal distances would be necessary. The most common applications are heavy plates inspection.

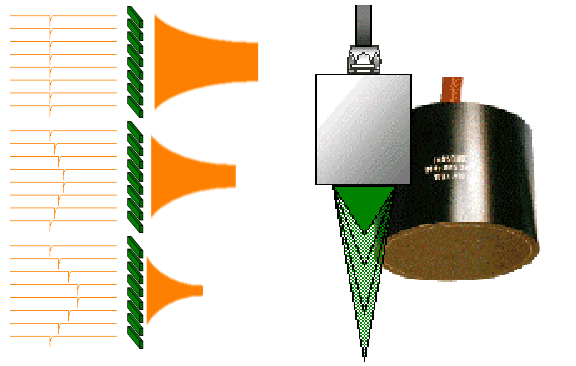


Figure 2 : Diagrammatic view of electronic focusing: electronic delay laws are applied (left) to focus the beam

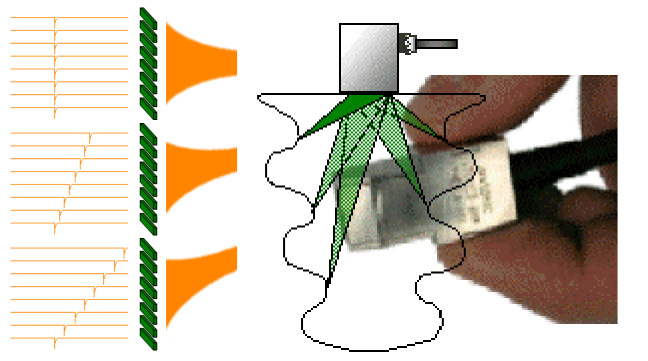


Figure 3 : Diagrammatic view of electronic deflection: electronic delay laws are applied (left) to deflect the beam

Electronic deflection

Electronic deflection, illustrated in figure 3, uses delay laws for electronic focusing. In this case, they are calculated to give the emitted beam an angle of incidence which can be varied simply by modifying the delay law (all the delays applied to each of the concerned channels).
Electronic focusing enables only one probe to be used for inspections traditionally requiring several probes working at different angles. In addition, it allows the beam to be deflected without using a wedge, allowing parts to be inspected from very small spaces.(3)

Electronic scanning, focusing and deflection can be combined to resolve applications such as the inspection of welds or tubes. Examples will be dealt with in the paragraph "Examples of applications" below.

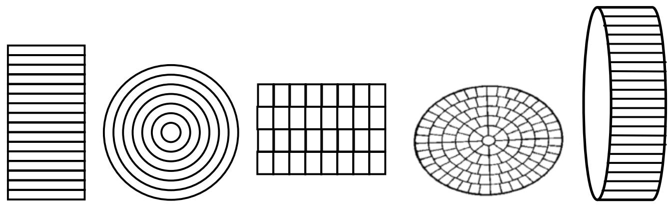
Phased array probes

Phased array technology requires the use of multi-element probes with variable geometry, but must also meet certain criteria :
Elements must be able to be driven individually and independently, without generating vibration in nearby elements due to acoustic or electrical coupling.
The performance of every element must be as close as possible in order to ensure the construction of a homogeneous beam.
Imasonic, thanks to its Piezocomposite 1-3 technology (1) and to its multi-element probe construction technology, designs and manufactures probes that meet these two criteria (2).

Figure 4 shows the different possible geometries of the multi-element probes described below.

Figure 4 : Examples of geometries of phased array transducer elements:

1. Linear array
2. Annular array with uniform pitch (non constant surfaces)
3. Matrix arrays (checkerboard and sectored rings)
4. Circular array



1 2 3a 3b 4

Linear array probes

These probes are made up of a set of elements juxtaposed and aligned along an axis. They enable a beam to be moved, focused, and deflected along a plane. Two examples of linear phased array probes are shown in figures 1 and 3.

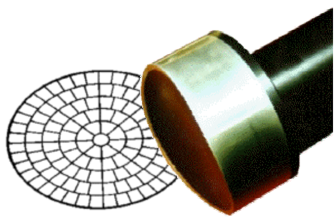
Annular array probes

Annular array probes are made up of a set of concentric rings. They allow the beam to be focused to different depths along an axis. The surface of the rings is in most cases constant, which implies a different width for each ring. An example of annular array probe is shown in figure 2.

Matrix array probes

These probes have an active area divided in two dimensions in different elements. This division can, for example, be in the form of a checkerboard, or sectored rings. These probes allow the ultrasonic beam to be driven in 3D by combining electronic focusing and deflection. An example of matrix array probe is shown below in figure 5.

Figure 5 : FERMAT matrix probe for inspecting titanium billets using the time reversal mirror technique (M.Fink ESPCI)



Circular array probes

These probes are made up of a set of elements arranged in a circle. These elements can be directed either towards the interior, or towards the exterior, or along the axis of symmetry of the circle. In the latter case, a mirror is generally used to give the beam the required angle of incidence (see figures 6 and 7).

Figure 6 : Principle of a tube inspection from the inside with a 10MHz 128-element flat circular array and a mirror

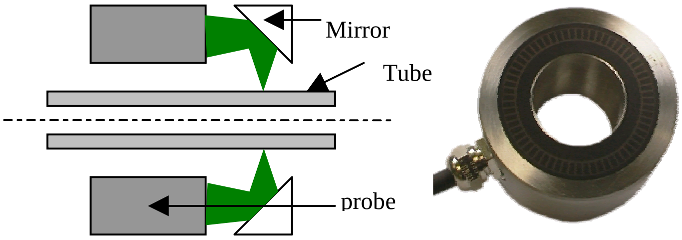


Figure 7 : Principle of tube inspection from the outside with a 10MHz 128-element flat circular array and a mirror

Main characteristics

Beyond their geometry, Phased Array probes offer the same flexibility of use as single-element probes. They can be used in immersion or in contact, their active area can be flat or focused, and they can also take into account the strong constraints of the industrial environment, such as temperature, pressure, vibration and radiation.

Examples of applications

Inspection of CRD from inside the control rod housing in BWR

The purpose of the inspection is to detect and size circumferential cracks open to the external surface in the stub tube and the housing of the CRD. The inspection is carried out from inside the control rod housing. The geometry of the component is illustrated in figure 8.
Two successive methods were implemented by Tecnatom to improve inspection performances.
The use of an annular array probe with rotating mirror, allowing to change the angle of inspection with the inclination of the mirror, and the focusing range with the electrical focusing. This method is illustrated in figure 9 below.
The use of contact linear array probes , allowing an increase of the inspection volume by inspecting the stub tube and the housing, allowing the complete inspection in one scan, and allowing the use of last innovations of the array technology in data acquisition systems and evaluation and simulation programs, while maintaining the quality standards of previous developments. This method is illustrated in figure 10.

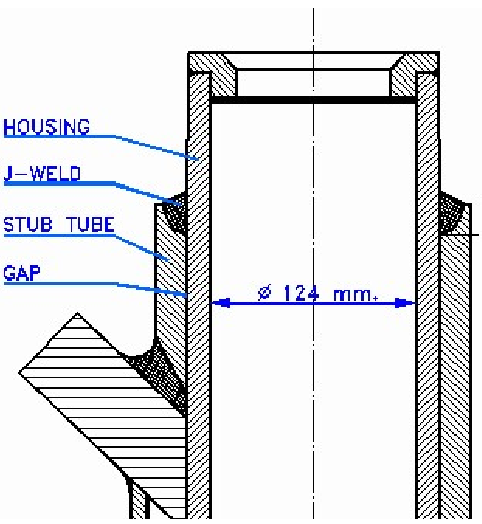


Figure 8 : description of the component geometry

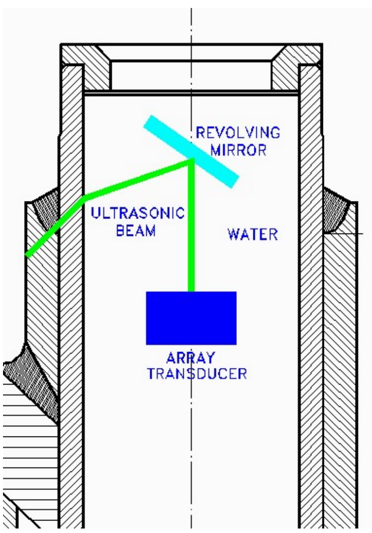


Figure 9 : inspection with annular array and rotating mirror

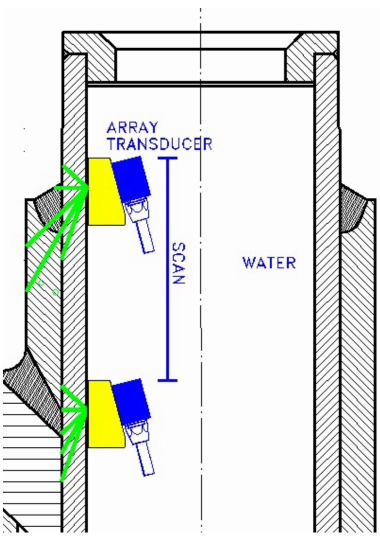


Figure 10 : inspection with contact linear phased array probe

Inspection of BWR nozzles from the outside

The objective of this inspection is to detect thermal fatigue-induced cracks in the nozzles of boiling water reactor (BWR) vessels, during inspections performed from the outer surface of the vessel.

From the ultrasonic point of view the main difficulties to be addressed were as follows:
The inspection of a geometrically complex volume from a no less complex scanning surface.
The results analysis, especially with regard to the positioning and sizing of defects.

The ultrasonic techniques selected by Tecnatom for the inspection with the array probes were those related to the contact pulse-echo method. The array probes used were of 16 crystals and frequency of 2 MHz. The techniques used in this case are illustrated in figure 11.

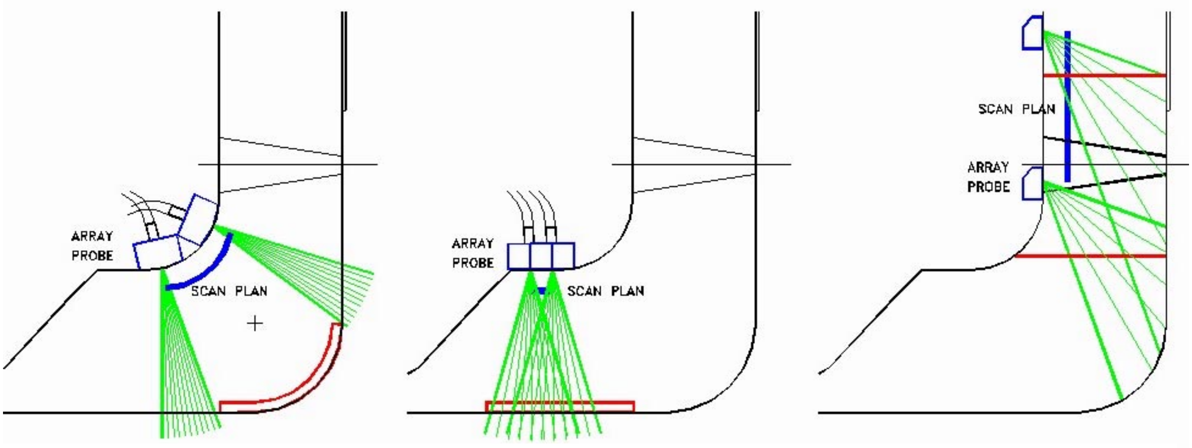


Fig. : schematic representation of Nozzle inspection from the outside with linear phased array probes

The method was developed using simulation programs for ultrasonic beam characterization and focal laws calculation. Other simulations were implemented to calculate the scan plans.

- The technique was validated on a mock up with notches representing possible defects.
- The advantages of this phased array based inspection technique are
- The reduction of the number of mechanical devices, probes and wedges
- The development of an effective defect sizing procedure
- The reduction of inspection times and doses

In service Inspection of turbine blades grooves through the central bore

The objective of this inspection is to detect thermal fatigue-induced cracking in the turbine blade grooves of medium and high pressure turbine rotors. The geometry of the components to be inspected is shown in fig. 12.

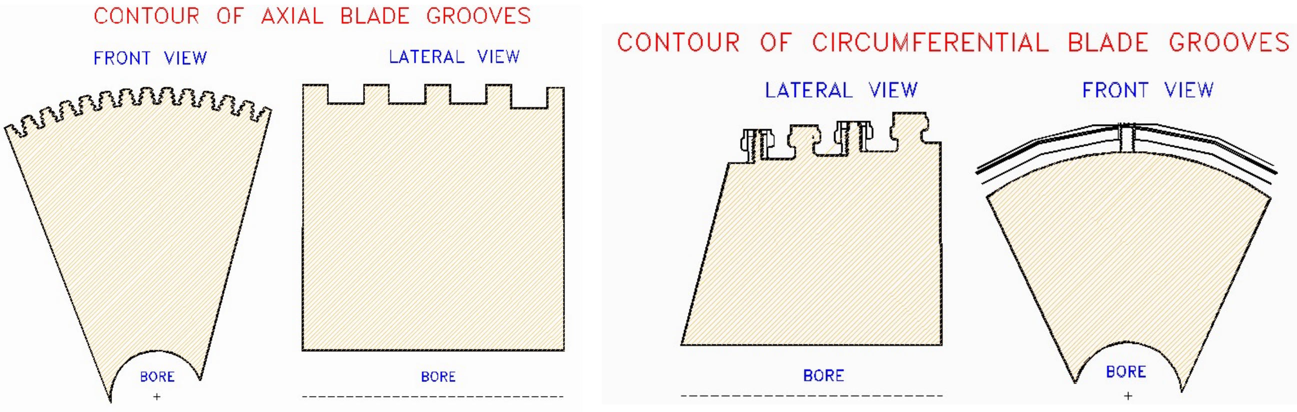


Figure 12 : geometry of inspected blades

The main difficulties to be faced from the ultrasonic point of view were as follows:
- The lengthy sound path through the material.
- The large difference in the thickness of the different crowns.
- The limitations on the ultrasonic beam access to the entire volume of interest from the central bore.

The ultrasonic technique selected by Tecnatom for development with array probes was the immersion pulse-echo method, with light oil being used as the intermediate fluid. Following definition of the defects considered as being critical, it was decided that three array probes would be required for detection: Two 0º and 15º longitudinal wave probes and one 45º transverse wave probe. The 0º probe would be used to detect defects in both types of blade grooves, while the other two would be used only for "T"-shaped circumferential blade grooves.
Three probes were designed and manufactured by Imasonic, these having an external diameter of 100 mm in order to have a small focus diameter in the area of interest. The active surface of these three probes is Fermat curvature shaped to correct the distortion of the ultrasonic beam that occurs when this beam impinges on the interface between the steel and the oil. In addition, the 0º probe was designed and manufactured with 16 annular rings with a view to allowing for variable focussing and thus be able to cover the different thicknesses corresponding to the two types of blade grooves. Figures 13 shows one of the three probes.

The three probes were attached to a probe-holding module. This device makes it possible to carry out all the acquisitions in one scan, without the need to lose time emptying and refilling the central bore with oil. figure 14 shows the probe-holding module used. Circumferential scanning is performed by rotating the rotor through 360º.

Figure 13 : Wide aperture annular array probe (100mm) with shaping of the

Figure 14 : three probes on the probe holder

The technique developed has been validated using the calibration block. The results obtained were highly positive, since all the defects present in the aforementioned block were detected. The manufacturer has accepted this ultrasonic procedure for the inspection of turbine blade grooves, as a replacement for the technique previously used which implied extracting, destroying and replacing the blades. Inspections have been carried out in thermal power plants, demonstrating the applicability of this technique.

The advantages of applying these inspection techniques are as follows:
- A destructive testing method is replaced by a non-destructive technique.
- Inspection times are reduced.
- It is possible to inspect 100% of the grooves.
- In case of repair it would be possible to determine the position of the damaged sector accurately, thus avoiding the unnecessary extraction of blades.

Inspection of turbine blade grooves (dovetail type) from the outer surface

The objective of this inspection is to detect thermal fatigue cracks in the turbine blade dovetail type grooves. The geometry of these components in shown in figure 15. The technical objective was to develop an inspection technique able to guarantee the detection of all possible defects to be found in these components.

By using different simulation programs some features such as the inspected volume, possible interferences and probes position were studied. In this way the optimal incidence on the defects was guaranteed. During the design phase, it was taken into account the fact that the geometry of these components is not always well known. Therefore the ultrasonic technique should provide information about this geometry.

In order to meet all the requirements, a phased array probe with 32 crystals was selected. This probe was coupling to the inspection surface by means of a wedge. Different transversal waves were used to assure the defects detection. The range of these waves was from 25º to 65º with increments of 1º. In this way all the volume could be inspected only in one steering from each angular position of the turbine disk. Moreover in this way valuable information about the geometry was obtained. Figure 15 illustrate this technique.

Mock-ups with defects of 1 mm, 2 mm and 3 mm depth were used in the development of the project and validation of the technique. Figure 16 shows the image of an acquisition with all angles, where the profile of the mock-up has been drawn. Figure 17 shows the acquisition of three of the notches existing in one of the mock-ups.

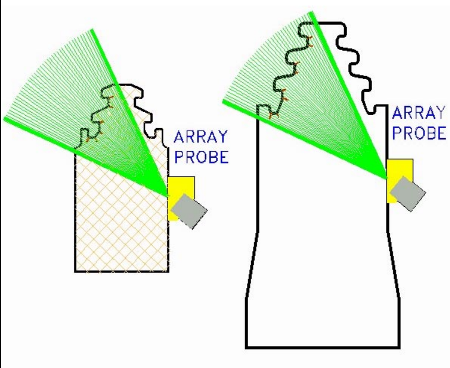


Figure 15 : schematic representation of blade grooves geometry and inspection technique

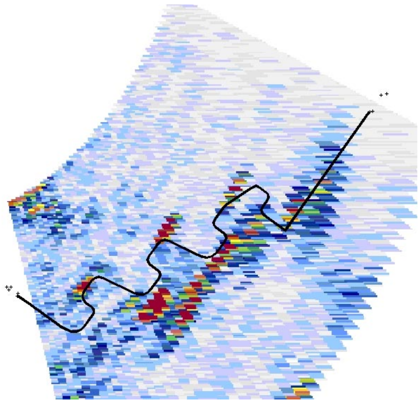


Figure 16 : schematic representation of blade grooves geometry and inspection technique

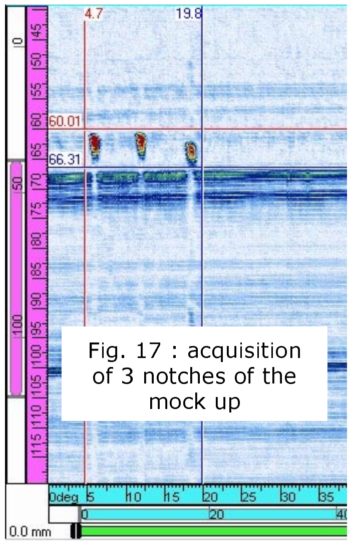


Fig. 17 : acquisition of 3 notches of the mock up

The advantages of using these techniques are:

- A destructive testing method is replaced by a non-destructive technique.
- Inspection times are reduced.
- It is possible to inspect 100% of the grooves.
- In case of repair it would be possible to determine the position of the damaged sector accurately, thus avoiding the unnecessary extraction of blades
- Maintenance costs of these components have been reduced significantly.

Conclusion

The advantages of using Phased Array technology are the technical and economic benefits gained:

- traditional mechanical scanning is replaced by the much faster electronic scanning
- electronic focusing allows the use of a single probe for working at different depths
- electronic deflection allows the angles of incidence to be varied with only one probe.
- Costs are thus significantly reduced because of the inspection and adjustment time saved.

In addition, phased array technology has made some applications possible that could not be resolved by traditional solutions, for example, when beam deflection is necessary without enough space to use a wedge (rotor steeple and blade root inspection) or when scanning is necessary without enough space for the corresponding mechanics (inspection of bent small-diameter tubes from the inside).

References

(1) A.Garcia, J.Vazquez, TECNATOM, " Applications of the phased array technique" (2001)

(2) J.Poguet, G.Fleury, J.L.Guey, P.Conche, IMASONIC, « Piezocomposite technology: An innovative approach to the improvement of N.D.T. performance using ultrasounds », proceedings of 3rd int. Conference on NDE relative to Structural integrity of Pressurized components (Seville 2001)

(3) J.Poguet, J.Marguet, F.Pichonnat, L.Chupin, IMASONIC, «Phased Array technology: concepts, probes and applications», proceedings of 3rd int. Conference on NDE relative to Structural integrity of Pressurized components (Seville 2001)

(4) J.Poguet, G.Fleury, O.Burat, G.Moreau, FRAMATOME "Circular phased array probes for inspection of Superphoenix steam generator tubes" Proc. Of EPRI Phased Array inspection seminar (1998)

(5) M.Fink, N.Chakroun, F.Wu, L.Beffy, G.Mangenet, « Application of ultrasonic time reversal mirrors to non destructive testing » Proceedings of 6th European Conference on NDT (Nice 1994)