ADVANCED UT TECHNIQUES

*Ivan **GRGA**, HRID d.o.o., Zagreb, CROATIA, 091/5076394; ivan.grga@hrid-ndt.hr*
*Fran **JARNJAK**, HRID d.o.o., Zagreb, CROATIA, 099/2707460; fran.jarnjak@hrid-ndt.hr*

ABSTRACT – *Ultrasonic phased array testing is a powerful NDT technology and one whose use is growing rapidly. The paper gives an overview on how an UT beam is formed using phased array compared to sound beams in conventional UT, presenting benefits introduced as well as disadvantages of ultrasonic phased array technology.*

Keywords: *non-destructive testing, ultrasonic, phased array, transducer, linear array, matrix array*

1. INTRODUCTION

Ultrasonic phased array testing is a powerful NDT technology and one whose use is growing rapidly. An array transducer is simply a transducer that contains a number of separate elements in a single housing. Phasing refers to how those elements are sequentially pulsed. A phased array system is normally based around a specialized ultrasonic transducer that contains many individual elements (typically up to 256) that can be pulsed separately in a programmed pattern. These transducers may be used with various types of wedges, in a contact mode, or in immersion testing. Their shape may be square, rectangular, or round, and test frequencies are most commonly in the range from 1 to 10 MHz.

2. CONVENTIONAL UT

2.1. Conventional UT transducer structure

Conventional ultrasonic transducers for NDT commonly consist of either a single active element that both generates and receives high frequency sound waves, or two paired elements, one for transmitting and one for receiving. Transducers come in a wide variety of sizes, frequencies, and case styles, commonly having a similar internal structure. The active element of the transducer is typically a thin disk, square, or rectangle of piezoelectric ceramic that converts electrical energy into mechanical energy (ultrasonic vibrations), and vice versa. A wear plate or acoustic lens protects is from damage. The transducer is backed by a block of damping material that quiets the transducer after the sound pulse has been generated. This ultrasonic subassembly is mounted in a case with appropriate electrical connections. Common contact, delay line, immersion, and angle beam transducers utilize this basic design (**Figure 1**). Dual element transducers have two separate transmitting and receiving elements mounted inside the housing at an angle to each other where one is optimized for transmitting and the other for receiving ultrasonic waves. The elements are separated by a sound barrier, transducers have no backing, and have an integral delay line rather than a wear plate or lens (**Figure 2**).
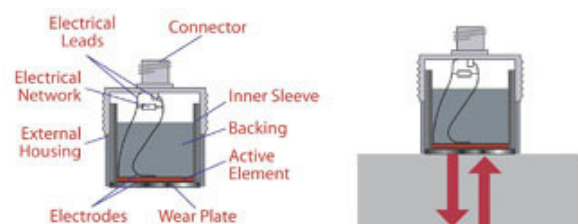

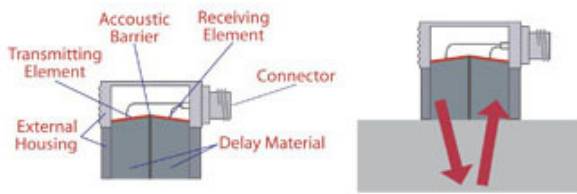**Figure 1** *Single element transducer.*

Figure 2 Dual element transducer.

Probe assemblies usually also include a plastic wedge. Wedges are used in both shear wave and longitudinal wave applications.

2.2. Conventional UT transmitting

The ultrasound that emanates from a conventional UT transducer (monocrystal probe) does not originate from a single point but from many points along the surface of the piezoelectric element (Huygens' principle). The end result is a sound field with many waves interacting or interfering with each other (*Figure 3*).
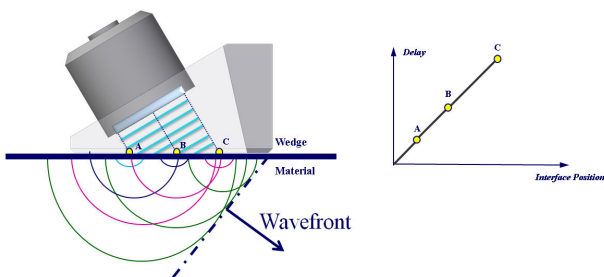

Figure 3 Conventional UT transmitting.

Element inside the transducer will generate a wavefront traveling at the velocity equal to the speed of sound in the wedge material. Due to wedge angle points of the wavefront (A, B, C) will reach wedge/material interface at different times and will each act as spherical wave generator.

These new waves will be traveling at a different speed due to the change of the material (medium). Wedge introduces delays and coupled with the ratio between velocities (Snell's law) will determine new direction (angle) of the wavefront in the material under test.

2.3. Conventional UT receiving

In receiving mode, waves hit the wedge/material interface at different times (points

A, B, C), so wedge (light gray) acts as a delay line which is forming a wavefront going towards the element (gray). (*Figure 4*)
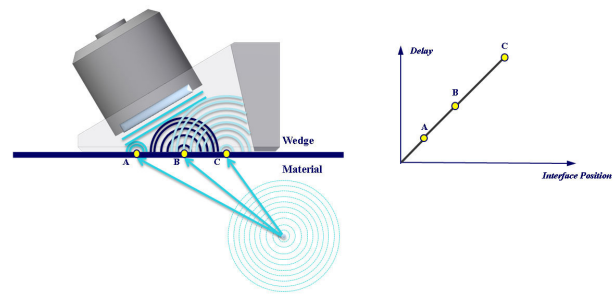

Figure 4 Conventional UT receiving.

2.4. Conventional UT sound beam

When performing inspections at 0 degree, all waves are in phase and add-up to a wavefront which creates the ultrasound beam. Since the beam is created by a number of points along the transducer face, the ultrasound beam intensity along the beam axis is affected constructive and destructive wave interference. These interactions lead to extensive fluctuations in the sound field intensity near its source, this defined the near field area. At the end of the near field, sound field becomes more uniform with one point containing maximum acoustic energy – focal point. This field called far field is more suited for detection and sizing and therefore a probe is selected to inspect material which is located in the far field.

In case of angle beam transducers, most wedge designs are done in such a way that the near field is contained within the wedge (*Figure 5*).
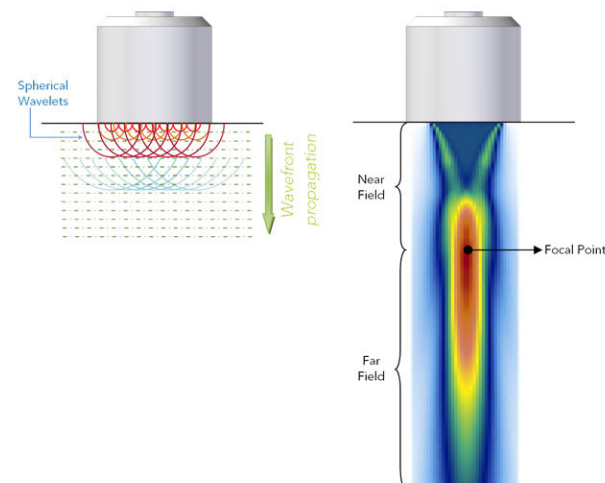

Figure 5 Conventional UT sound beam.

3. PHASED ARRAY (PA)

A phased array system utilizes the wave physics principle of phasing, varying the time between a series of outgoing ultrasonic pulses in such a way that the individual wave fronts generated by each element in the array combine with each other to add or cancel energy in predictable ways that effectively steer and shape the sound beam.

The programmed pattern of time delays applied to pulsing and receiving from the individual elements of an array transducer in order to steer and/or focus the resulting sound beam and echo response are called focal laws.

Using focal, different desired effects like beam steering, focusing, aperture control, electronic scanning can be produced.

Therefore PA allows for customization of probe function depending on the specific application demands by modifying parameters only in software/instrument while physical probe remains the same.

Phased array probes are found in two main configurations: 1D and 2D.

3.1. Phased Array 1D Linear Array

1D Linear array is the most common type of design and it allows for: beam steering, focusing and electronic scanning (**Figure 6**).
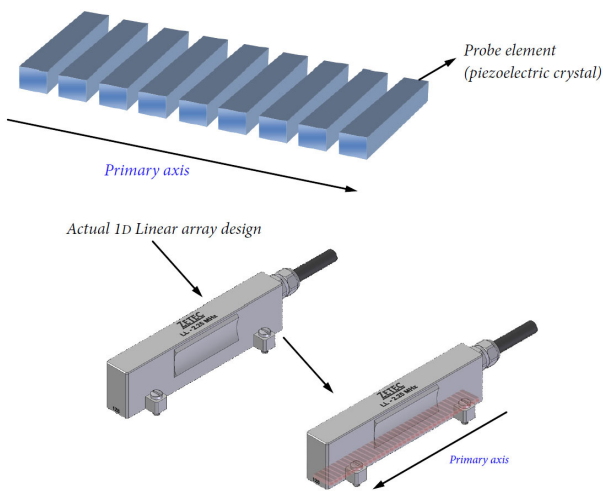

Figure 6 1D Linear Array.

Most system will allow you to use a single probe for pulse-echo inspection or two for pitch & catch configuration. You can also define tandem (pitch & catch) configuration with a single probe for specific applications (**Figure 7**).
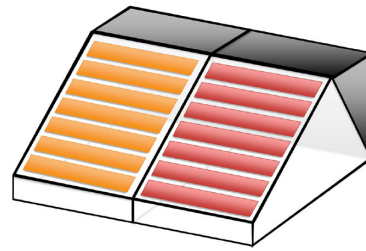

Figure 7 1D Linear Array in pitch & catch configuration.

3.2. Phased Array 2D Matrix Array

Standard 2D matrix array are very versatile probes that allow focusing, steering and skewing your ultrasound beam depending on the configuration of the probe (**Figure 8**).
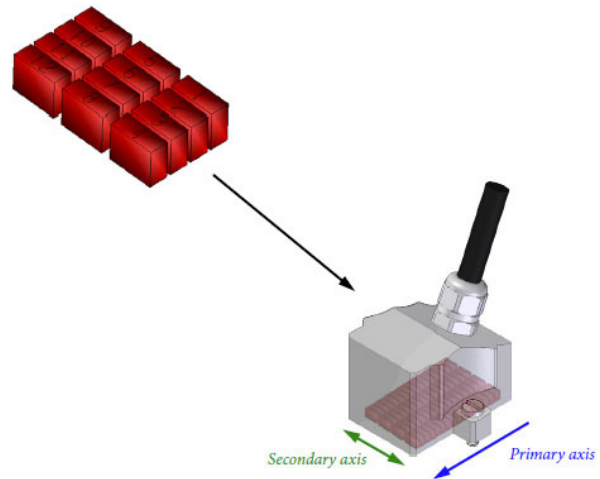

Figure 8 Standard 2D Matrix Array.

Except most common 1D and 2D linear arrays, PA transducers can be made in other shapes for optimizing UT inspection in specific applications (**Figure 9**).
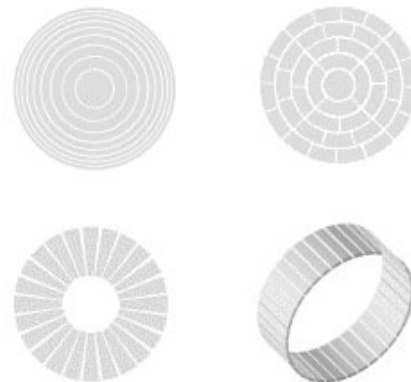

Figure 9 Annular array, Annular sectorial array, Daisy array, Circular array.

3.3. Phased Array sound beam

With PA transducers, if each element is pulsed at the exact same time, resulting beam will be the equivalent to the beam generated by conventional UT probe of the same aperture – created by the sum of all the individual beams generated by each element (**Figure 10**).

Applying delays on when each element is pulsed (focal law) gives PA its benefits – steering, focusing, aperture control.
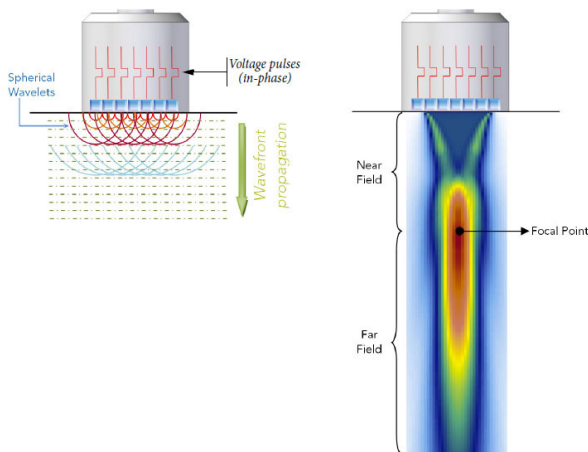

Figure 10 *Annular array, Annular sectorial array, Daisy array, Circular array.*

3.4. Phased Array element excitation

Phased array principle is that each element inside the PA probe is activated with a delay to produce desired UT beam. (**Figure 11**)
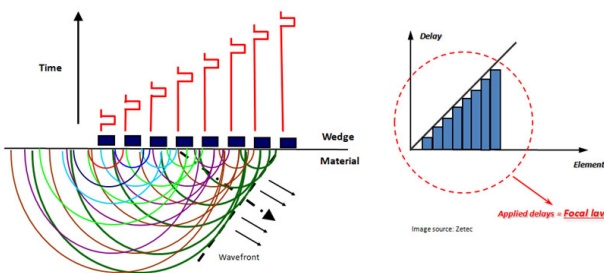

Figure 11 *Phased array angle beam wave forming.*

A phased array probe consists of a series of piezo-composite elements, which can be excited independently one from the others. By precisely controlling the time delays between the excitation of the individual elements, ultrasonic beams of various angles, focal distances and aperture can

be transmitted in the inspected specimen (**Figure 12**). The returning echo from a reflector is detected by each elements of the PA probe at a slightly different time. The individual echo signals are then time-shifted before being summed up. The result of this process is an A-scan that emphasizes the response from the desired focal point (**Figure 13**).
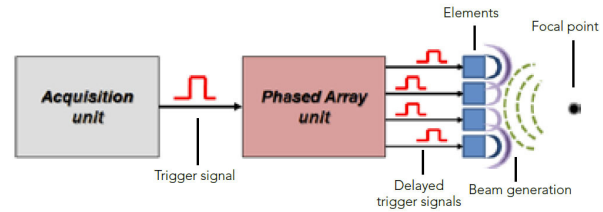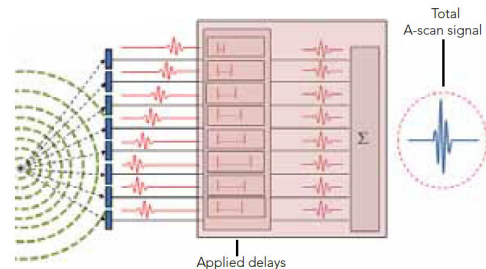

Figure 12 *Beam emission.*

Figure 13 *Signal reception.*

3.5. Characteristics Modifications

PA inspection technology is based on multiplexing of a large number of crystals (elements inside the PA probe) to operate as a desired single crystal probe. It allows control of aperture size and position (beam width and linear electronic scanning), focal depth and steering angle.

3.5.1. Aperture

Maximum aperture size is based on instrument limitations. Each instrument configuration allows you to control a maximum number of active elements and a maximum number of elements that can be connected. For example: 32/128 instrument means it can have up to 32 active channels out of 128 supported. 32 channels can be activated at the same time to apply a focal law. Other 96 channels are not active, but 32 of them can be activated in the next time period.

Modifying the aperture size by a factor x2, will change the Near Field length for the
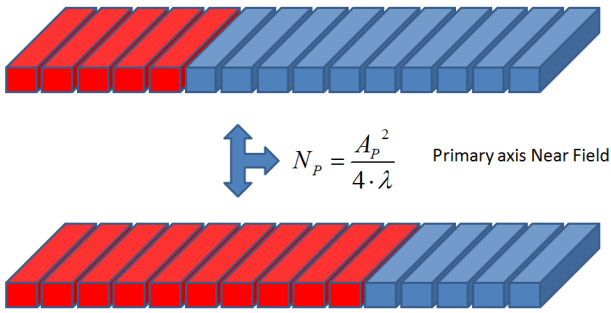
primary axis of the probe. (**Figure 14**).

Figure 14 *1D Linear Phased Array probe aperture.*

With a 2D probe, you can modify the aperture size along the primary but also the secondary axis (**Figure 15**).
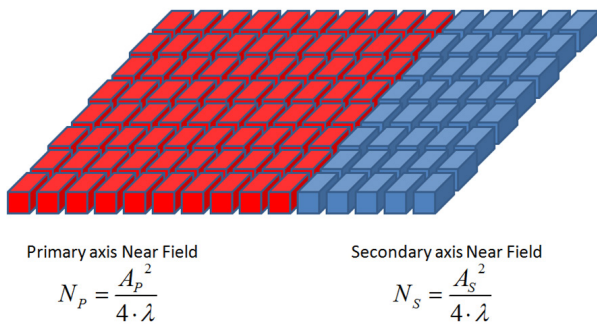

Primary axis Near Field
$$N_P = \frac{A_P^2}{4 \cdot \lambda}$$

Secondary axis Near Field
$$N_S = \frac{A_S^2}{4 \cdot \lambda}$$

Figure 15 *2D Matrix Phased Array probe aperture.*

Such probe can provide multiple refracted angles but also multiple skewing angles. Beam characteristics will depend on number of elements used.

Near Field length is calculated the same way as with a conventional probe – replacing the diameter by the length of the aperture along the considered axis (just like conventional rectangular UT probe). Final Aperture will determine the limitation of the focusing capability of the emitted beam.

One strength of PA technology is the ability to select the area of the probe that will produce the beam or overall move the aperture along the probe instead of moving a conventional probe back & forward, toward a weld for example.

3.5.2 Beam focusing

Beam focusing allows for focusing at several depths, using a single probe with parabolic focal laws. It is limited to near-field only (in emission) and can only be performed on the primary axis when using a 1D array.

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.

The near field length and hence the natural divergence of an ultrasonic beam are determined by aperture (equal to element diameter in the case of conventional monolithic transducers) and wavelength (wave velocity divided by frequency). (**Figure 16**)
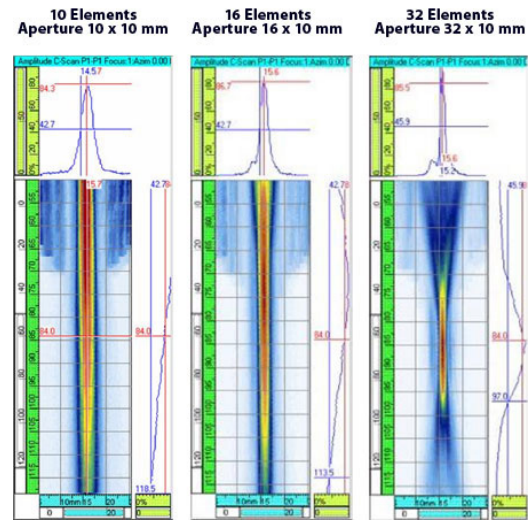

Figure 16 *Increasing the aperture size increases the sharpness of focused beam*

As the element diameter and/or frequency increase, the beam spread angle decreases. A smaller beam spread angle in turn can result in higher effective sensitivity in the far field zone since the beam energy dissipates more slowly (**Figure 17**).
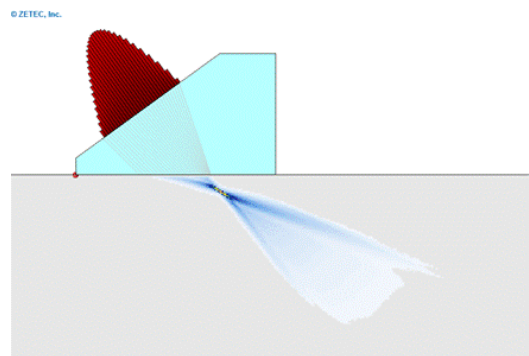

Figure 17 *Beam focusing.*

Within its near field, a transducer can be focused to create a beam that converges rather than diverges.

Narrowing the beam diameter to a focal point increases sound energy per unit area within the focal zone and thus increasing sensitivity to small reflectors.

3.5.3. Beam steering

Beam steering allows modification of the refracted angle and applies asymmetrical (e.g. linear) focal laws (*Figure 18*). It can only be performed on the primary axis when using 1D-arrays.

The basic idea behind the beam steering capability is to partially replace wedges in order to obtain angle beams.
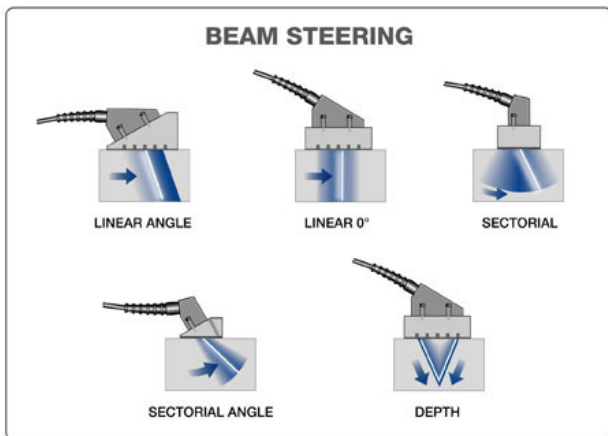

Figure 18 Beam steering.

For phased array transducers, the maximum steering angle (at -6 dB) in a given case is derived from the beam spread equation.

$$\sin \theta_{st} = 0.514 \, \frac{\lambda}{e}$$

$\sin \theta_{st}$ = sine of the maximum steering angle
λ = wavelength in test material
e = element width

Small elements have more beam spreading and hence higher angular energy content, which can be combined to maximize steering. As element size decreases, more elements must be pulsed together to maintain sensitivity (more channels on the instrument are needed).

When the element number is constant, the maximum beam steering angle increases as the aperture size decreases (*Figure 19*).
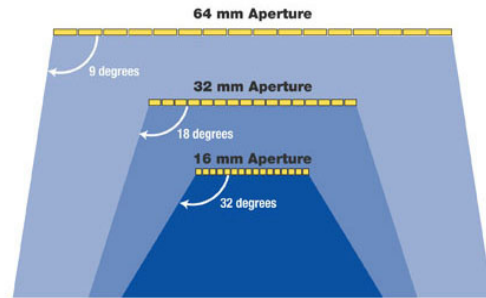

Figure 19 Beam steering limits.

3.6. PA Technology advantages

Phased Array Technology allows you to use more angles and increase your probability of detection (misoriented flaws). (*Figure 20*)
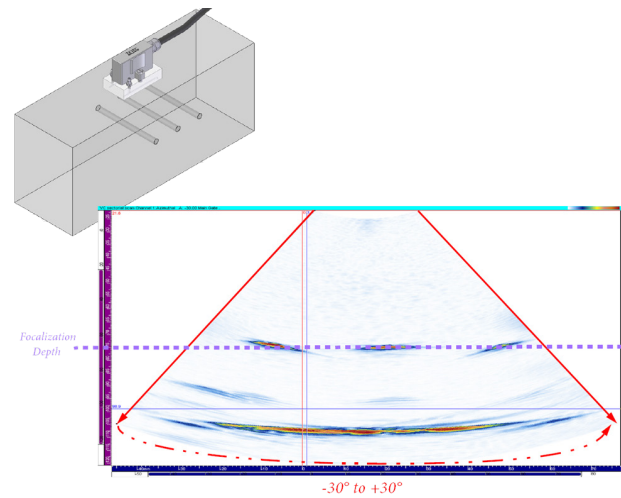

Figure 20 More angles.

For a lot of configurations, it allows you to be faster by covering all your angles with a single probe or performing electronic scanning to cover wider and faster. The main thing is optimization – allowing you to tackle more effectively challenging applications (*Figure 21*).
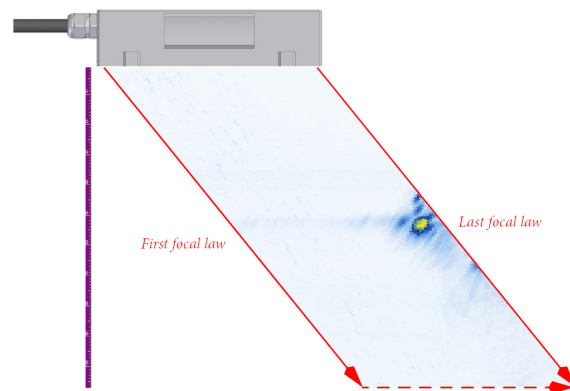

Figure 21 Electronic scanning.

Reduction of probe count allows reduction in cabling, probe sled size manipulator size as well.

3.7. PA Technology disadvantages

PA Technology also has some disadvantages. Higher cost resulting for more expensive probes than conventional UT probes. The cost of equipment and cabling is also higher. There is also an increase in UT data storage requirement.

Another phenomenon associated with phased array probes as well as with conventional transducers 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 (*Figure 22*).

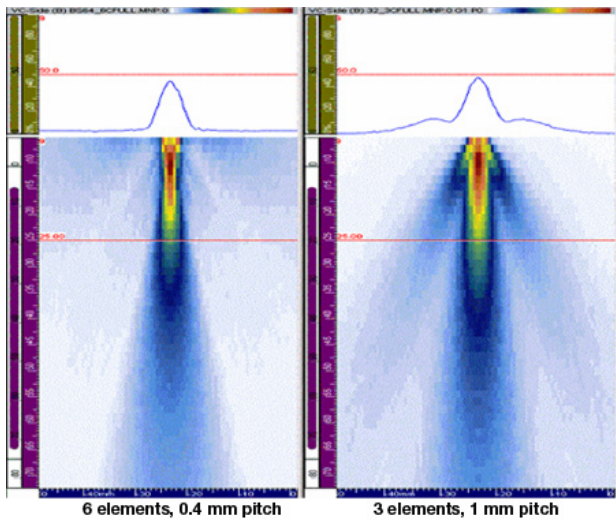**6 elements, 0.4 mm pitch**   **3 elements, 1 mm pitch**

Figure 22   Grating lobes.

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. The simplest way to minimize grating lobes in a given application is to use a transducer with a small pitch. Specialized transducer design incorporating subdicing (cutting elements into smaller elements) and varying element spacing will also reduce unwanted lobes.

4. APPLICATION

During their first couple decades, commercial ultrasonic instruments relied entirely on single-element transducers that used one piezoelectric crystal to generate and receive sound waves, dual element transducers that had separate transmitting and receiving crystals, and pitch/catch or through transmission systems that used a pair of single-element transducers in tandem. These approaches are still used by the majority of current commercial ultrasonic instruments designed for industrial flaw detection and thickness gauging, however instruments using phased arrays are steadily becoming more important in the ultrasonic NDT field.

HRID recognized the growing importance of phased array and is currently in the phase of qualifying UT phased array techniques for NDT inspection of the following systems at Novovoronezh NPP and Leningrad NPP in Russia:

- Inspection system for steam generator tubes, collector ligaments and collector welds

- Inspection system for reactor pressure vessel and its internals from inside

- Inspection system for shell of main circulation pump

- Inspection system for flange of reactor pressure vessel

- Inspection system for bolts from M36 to M170

- Inspection system for threads from M36 to M100

- Inspection system for circumferential welds on pipes

- Inspection system for pipe elbows

- Inspection system of welds on shells on primary circuit components

5. CONCLUSION

The benefits of phased array technology over conventional UT come from its ability to use multiple elements to steer, focus and scan beams with a single transducer assembly.

Beam steering, commonly referred to as sectorial scanning, can be used for mapping components at appropriate angles.

Beam steering permits multiple angle and/ or multiple point inspection from a single probe and a single probe position.

With beam steering both longitudinal and transversal (shear) waves can be generated using a single probe.

Electronic focusing permits optimizing the beam shape and size at the expected defect location, as well as further optimizing probability of detection. The ability to focus at multiple depths also improves the ability for sizing critical defects for volumetric inspections. Focusing can significantly improve signal-to-noise ratio in challenging applications, and electronic scanning across many groups of elements allows for C-Scan images to be produced very rapidly.

6. REFERENCES

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PRVA OBAVIJEST

IZBORNA GODIŠNJA SKUPŠTINA HDKBR-a

Održati će se 17.12.2013.(utorak) sa početkom u 13:00 sati u prostorijama HDKBR-a, Hrvatski inženjerski savez, Berislavićeva 6, Zagreb, soba broj 14, sa sljedećim dnevnim redom:

Prijedlog dnevnog reda:

1. Imenovanje radnih tijela skupštine
2. Prihvaćanje zapisnika sa zadnje skupštine
3. Prihvaćanje dnevnog reda skupštine
4. Izvješće o radu u protekloj godini
5. Dopune Statuta
6. Nagrade i priznanja
7. Razriješnica članova Upravnog odbora
8. Izbor Predsjednika društva
9. Izbor članova Upravnog odbora
10. Program rada
11. Različito