Ultrasonics

Part 12. Fundamentals of ultrasonic phased arrays

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Ultrasonic arrays are now widely used in underwater sonar and in more than 25% of medical scans but their use in non-destructive testing (NDT) has been much less common. However, the cost of the design and manufacture of electronics specifically for use with ultrasonic arrays for NDT has recently fallen very significantly. In addition, adaptation of the processes to design and manufacture arrays for medical imaging has taken place for NDT. Thus, two of the main components for the use of arrays for NDT are now readily available. The third important component is the understanding and standardisation of inspection procedures that will allow common use in routine NDT. Work towards this has begun. As part of this process, the present article is intended to assist the NDT practitioner to extend his or her existing knowledge of ultrasound probes and their use to ultrasonic arrays.

Full understanding of arrays is very complicated and previous publications often assume a high level of mathematical expertise and the ability of the reader to invest a lot of time in the topic. Instead, this article seeks to establish understanding of the fundamentals, allowing the interested practitioner to begin to access other resources to extend this understanding according to their choice. The article begins with a short review of conventional ultrasound probes and the basis of ultrasound from first principles, as a foundation for discussion of arrays. This foundation is then developed to take into account differences between conventional probes and ultrasonic arrays. The way an array works with electronics is described and the flexibility this provides for the NDT practitioner is emphasised. The article concludes with a list of advantages and disadvantages of ultrasonic arrays and their reasons.

Conventional ultrasound probes

Historically, most use of ultrasound in NDT has been based on single- or dual-element probes. An enormous range of such probes is available. These can generally be divided into two main classes:

- ☐ *Compression wave probes* generate ultrasound in which the local, almost negligible movement of particles in the test-piece, which is the basis of ultrasound, is in the same direction as the beam of ultrasound itself. Compression wave ultrasound generally travels at high speed and is the only type possible in liquids such as water.
- ☐ *Shear wave probes* generate ultrasound in which the movement of particles in the test-piece is at right angles to the direction of the beam of ultrasound. Shear wave ultrasound generally propagates more slowly than compression wave ultrasound and does not exist in liquids.

In both cases, a *pulse* of ultrasound is transmitted into the test-piece and any reflections which return to the probe from features such as a back-wall or a defect within the beam are detected as electrical signals.

As ultrasound occurs as local movement of particles in the test-piece, it is necessary for the particles eventually to return to their original position to avoid the test-piece being distorted. This is the basis of ultrasound as a *wave phenomenon*.

A particle in an ultrasound wave moves away from its original position a very small distance in a particular direction then moves back and away again in the opposite direction. This process is repeated, with the distances becoming smaller, until the wave dies away at that original position. However, particles nearby take up the motion and this is the basis of wave propagation.

A very important aspect of wave propagation is the *wavelength*. This is the distance between particles which are moving in the same way because of the ultrasound. Mathematically, the wavelength is related to the speed of the ultrasound and its frequency according to:

$$\lambda = v / f$$

where λ is the wavelength, v is the speed, and f is the frequency at which the probe is operating.

As compression wave ultrasound travels faster than shear wave ultrasound, it has a longer wavelength, typically approximately twice as long, for the same frequency.

To aid the practitioner, a mathematical example is used in this article. To begin with, a probe frequency of 5 MHz is assumed. In steel, the speed of compression waves can be taken to be 5900 ms^{-1} and the speed of shear waves to be 3230 ms^{-1} (1). Hence the wavelength of compression waves is 1.18 mm and the wavelength of shear waves is 0.646 mm.

Longer wavelengths are affected less by small features in the test-piece such as defects or the microstructure of the material itself. This means that, for a given frequency, compression wave ultrasound is less sensitive to small defects than shear wave ultrasound but it has better penetration. Thus, if a practitioner wants to achieve the same penetration with a shear wave probe as with a compression wave probe, a lower frequency should be used for the shear wave probe.

If the probe is a *dual-element* type, then one element is used for transmitting and the other for receiving. This has some advantages for system design and operation but makes no difference to the way ultrasound is generated in the test-piece or detected after it has reflected off a defect.

Any given single-element device of either the compression wave or shear wave type produces a beam in a fixed direction. With compression wave probes, this is most often at right angles to the surface of the test-piece with which the probe is in contact, and the probe is called a 0° probe, as illustrated in Figure 12.1(a). With shear wave probes, the beam is most often at a specified angle from the surface of the test-piece, such as 30°, 45° or 70°, as illustrated in Figure 12.1(b).

It is also possible to make a single- or a dual-element probe which *focuses* the beam of ultrasound. In this case, rather than having a beam in a particular direction which gradually spreads out,

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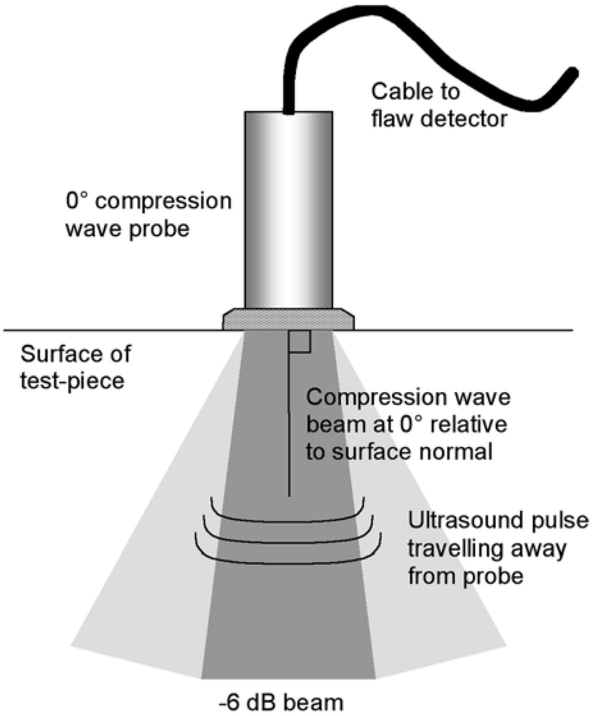

Figure 12.1(a). Schematic diagram of a 0° compression wave probe, showing the configuration of the beam at right angles to the surface of the test-piece

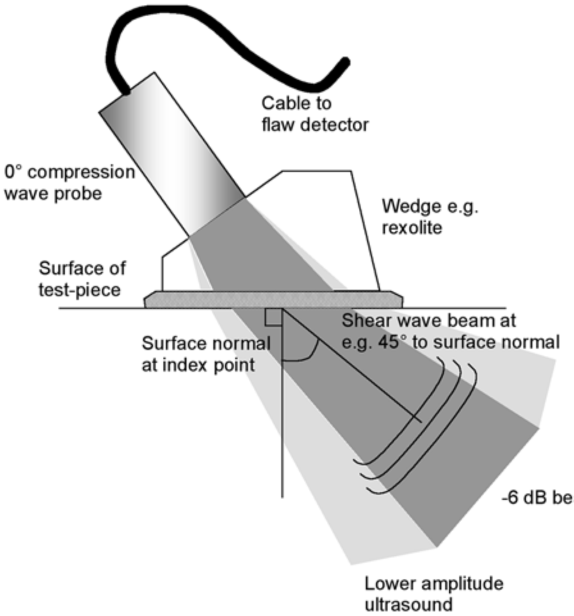

Figure 12.1(b). Schematic diagram of a 45° shear wave probe, showing the configuration of the beam on the wedge and in the test-piece

the beam is deliberately shaped so that the ultrasound converges at a particular distance from the probe, as illustrated in Figure 12.1(c). Focusing increases the sensitivity of the inspection as a defect at the focal point will be subject to a larger ultrasound signal and a larger electrical signal will be generated when the ultrasound reflection reaches the probe. However, this effect does not occur unless the defect is near the focus.

For some inspection procedures, the choice of probe is very easy. For example, a compression wave probe is ideal to measure the thickness of a simple flat test-piece. However, the use of conventional probes is more difficult in other situations.

As an example of a difficulty, if thickness measurement is needed at all points across the surface of a large test-piece, conventional use of a compression wave probe will take a long time. Another example is when the test-piece is a complicated fabrication which requires different inspection procedures in different places. In this case, several conventional probes may be needed. A third example is when it is necessary to have an electronic record of the condition of a test-piece with full area coverage. In this case, position sensing and digital signal recording are necessary.

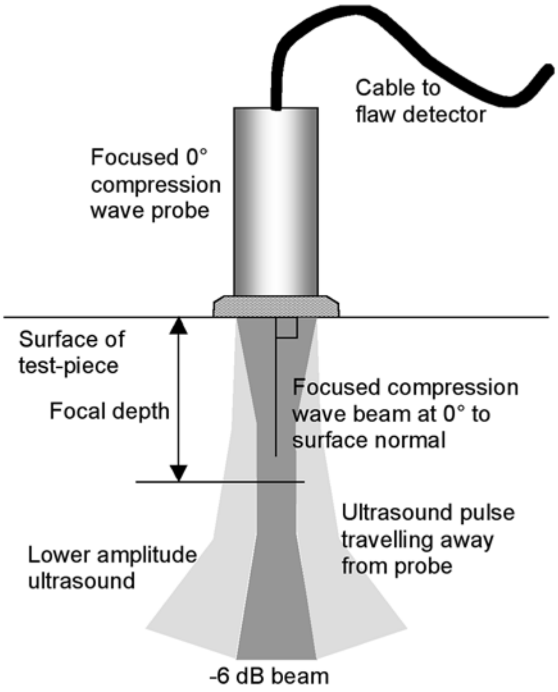

Figure 12.1(c). Schematic diagram of a 0° focused compression wave probe, showing how the beam narrows at the focal depth, in comparison with the unfocused probe shown in Figure 12.1(a)

The examples which have been outlined relate to the capabilities of conventional probes. In the next section, the capabilities of NDT with an ultrasonic array are described.

Capabilities of an ultrasonic array

An ultrasonic array is a probe which can be used in different ways to replace many different conventional probes and which can also behave in ways that are impossible with conventional probes.

(a) An ultrasonic array can be set up to behave as an unfocused electronically scanned compression probe. This allows much faster full area coverage than with a conventional compression wave probe.

(b) An ultrasonic array can be set up to behave as a focused compression probe with the focal depth scanned electronically. This maintains sensitivity to defects through a continuous range of depths.

(c) Using a *wedge*, an ultrasonic array can be set up to behave as an angle beam shear wave probe with the angle scanned electronically. This maintains sensitivity to defects around a continuous range of angles.

(d) An ultrasonic array can be set up to focus its beam and receive signals from a range of angles and at a range of depths, giving an inspection process which maintains sensitivity at all points in the scanning region within the test-piece.

(e) By combining the capabilities of the ultrasonic array, electronics and digital data recording, a full inspection of a test-piece can be carried out with a single physical scan. It is possible for the array then to mimic any conventional probe just by processing the data in different ways on a computer workstation.

(f) With careful control, a single ultrasonic array can act as a transmitting compression wave probe and a receiving shear wave probe in the same position. This allows *mode conversion* between compression waves and shear waves within the test-piece to be recorded.

Configurations (a) to (e) could be achieved with conventional probes, but only much more slowly and with results which might be significantly poorer. Configuration (f) is impossible with a conventional probe.

To explain how the capabilities of the array are realised, both the physical structure of the array and the electronics that are used with it must be considered. The physical structure is described in the next section.

Physical structure of an ultrasonic array

The physical structure of an ultrasonic array is shown schematically in Figure 12.2(a). From this diagram, it can be seen that the array is actually just a set of small probes arranged side-by-side in a single integrated package. This is the physical reality, but it is not much help in understanding how the array can work so flexibly. To explain this, a single one of the small probes, called an *array element*, is considered first.

The type of element considered here is shown in Figure 12.2(b). Like a conventional probe, it has a backing material to control the length of the pulse of ultrasound it produces, and a protective faceplate to prevent damage from contact with the test-piece. From Figure 12.2(b), it can be seen that the array element is much longer than its width. This means that when it is placed side-by-side with other elements a long line of elements is formed. This leads to the description of this type of array as a *one-dimensional* (1D) array.

Because of the shape of the element, the beam of ultrasound it produces has a broad cylindrical shape. This is also shown in Figure 12.2(b). The cylindrical beam of the array element means that ultrasound is transmitted away from it with relatively uniform amplitude at all angles in the test-piece. As a receiver, the array element is also sensitive to reflected ultrasound arriving back from any angle. This is different from a conventional probe, which usually produces a relatively narrow circular beam with an almost uniform, large amplitude within the beam and a very small amplitude outside it, as shown in Figure 12.1.

The beam width can be estimated mathematically using two different equations. For a conventional circular probe, the beam width defined by the points at which it has dropped by -6 dB from its maximum on both sides of the beam is given by$^{(2)}$:

$$\theta_c = 2 \sin^{-1} (0.70\, \lambda / \phi)$$

where ϕ is the diameter of the probe and for a rectangular probe such as a single element of an array, the beam width is given by:

$$\theta_r = 2 \sin^{-1} (0.44\, \lambda / l)$$

where l is the length of the side of the rectangle parallel to the plane in which the beam width is measured.

Putting in some figures, a 0° circular compression wave probe 10 mm in diameter has a -6 dB beam width in steel of approximately 10°. In the direction parallel to the length of an array element 10 mm long, the -6 dB beam width in steel is 6°. In the other direction, parallel to the width of the array element, assuming it is 0.5 mm wide, the estimated -6 dB beam width extends to ±90° on each side of the element. This shows that the beam perpendicular to the width of the array element is much wider than it is perpendicular to its length, corresponding to the description of the beam as cylindrical.

A single array element behaves just like a long narrow compression wave probe. However, if a number of elements are used side-by-side, all transmitting the same pulse at once, then the ultrasound beam from each element merges with the others to form a single beam, as illustrated in Figure 12.3. Thus, an ultrasonic array with all its elements interconnected will behave similarly to a 0° compression wave probe of the same size as the whole array.

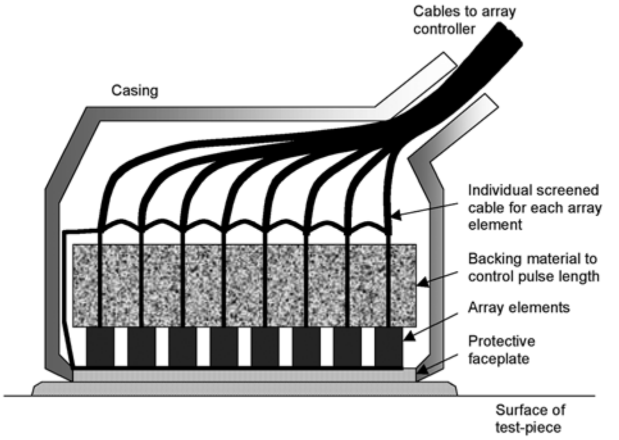

Figure 12.2(a). Schematic diagram of the internal structure of a phased array, shown from the side. The wiring layout in an actual array would be different and the details of the structure might also differ

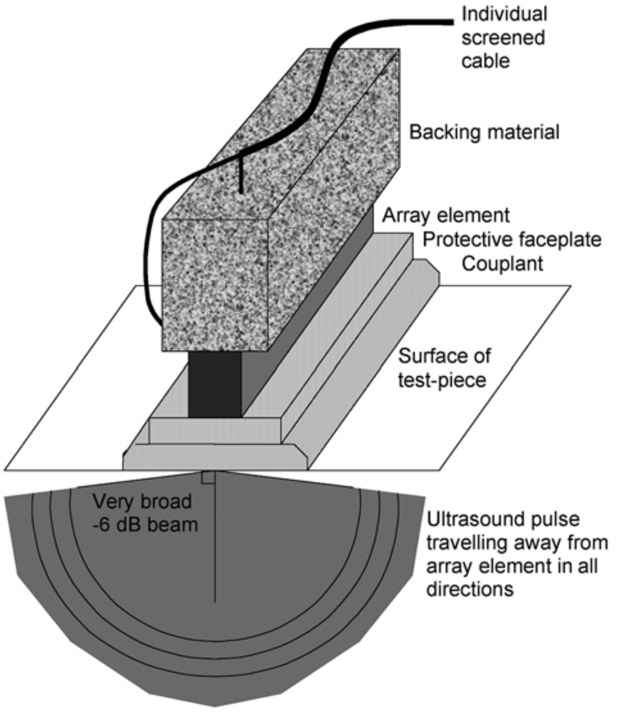

Figure 12.2(b). Schematic diagram of one element of a phased array, showing the element detail and indicating the compression wave beam pattern

The aperture of an array can be defined as the outer dimensions of the area covered by its elements, as shown in Figure 12.4. The length of the array is calculated as:

$$L = (N - 1)\, \delta e_{c\text{-}c} + w_e$$

where N is the number of elements in the array, $\delta e_{c\text{-}c}$ is the centre-to-centre spacing of the elements, and w is the width of an element. The *width* of the array, W_A, is equal to the *length* of an element. As an example, an array with eight elements each 0.5 mm wide, 10 mm long and with a centre-to-centre spacing of 0.6 mm, is 4.7 mm long and 10 mm wide.

Using the length and width of the array, it is possible to calculate the beam width for the array operating at 0°.

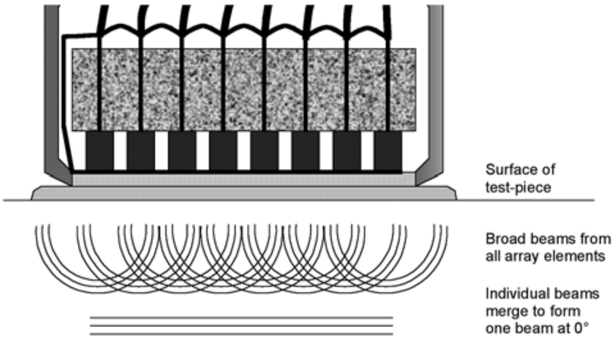

Figure 12.3. Diagram showing how the broad beams with cylindrical wavefronts emerging from the individual elements of a phased array merge together to form a single 0° compression wave beam

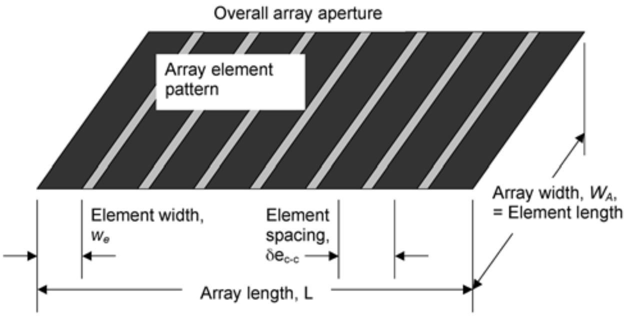

Figure 12.4. The aperture of a phased array operating at 0°. The dark areas are the elements and the overall shaded area indicates the total effective aperture of the array

Because the structure of the array is much more complicated than the structure of a conventional probe and because some of its dimensions are much smaller, it is much more expensive to make an array. The need for a cable containing many individual co-axial connections also increases the cost of the array. As a guide, an array may cost around ten times the price of a conventional probe of the same engineering quality. However, if the array can be made to behave like many different probes or if it can be used for an inspection which is otherwise impossible, then this price difference may not matter.

Now that the physical structure of the array has been described, the operation of the electronics can be understood. This is covered in the next section.

Electronics used with an ultrasonic array

Almost all ultrasonic arrays have a number of elements which is a power of two, such as 8, 16, 32 or 64. This is because it is usually easiest to design electronics, called an *array controller*, with a number of *channels* which is a power of two, with each channel behaving like a *separate digital pulser-receiver*.

The single most important difference between an array and a conventional probe is that, by connecting each element in the array to a separate channel in the array controller, it can be made to transmit or to act as a receiver at a slightly different time instant from the other elements. By setting up the array controller so that each channel operates at a different time instant, the NDT practitioner can control the way the transmitted pulses or received signals merge together. Thus, the array can be made to mimic different conventional probes.

As an example, consider an array with eight elements each 0.5 mm wide and with a centre-to-centre spacing of 0.6 mm which is to be used to produce a beam *steered* at an angle $\theta_s = 45°$ for a procedure such as weld inspection, as illustrated in Figure 12.5(a). To make the beams from all the array elements merge together at this angle, the element farthest away from the weld must produce a pulse of ultrasound first, then the element next farthest away, and so on until the nearest element is pulsed.

Mathematically, the difference in time between each element, δt, can be calculated using the formula:

$$\delta t = \delta e_{c\text{-}c} \sin \theta_s / f \lambda = \delta e_{c\text{-}c} \sin \theta_s / v$$

so that the element farthest from the weld is pulsed at time $t = 0$ s, the next element at $t = 60$ ns, and the element nearest the weld at time $t = 420$ ns. In this way, the array behaves like a compression wave probe producing a beam at 45°.

It is important to notice that the previous example is different from a conventional angle probe operating at 45° on a wedge as the conventional probe produces a shear wave beam whereas the array produces a compression wave beam. An array can also be used to produce a shear wave beam by operating it on a wedge. In this case, the calculation of the time delays is more complicated and software supplied with the array controller should be used to generate what is called a *focal law*.

As an example of focal law calculation, the arrangement in Figure 12.5(b) can be considered. To produce the focused beam shown there, in which the pulses of ultrasound produced by the array converge at a *focal point* 10 mm below the array, the same kind of calculation process as before can be used.

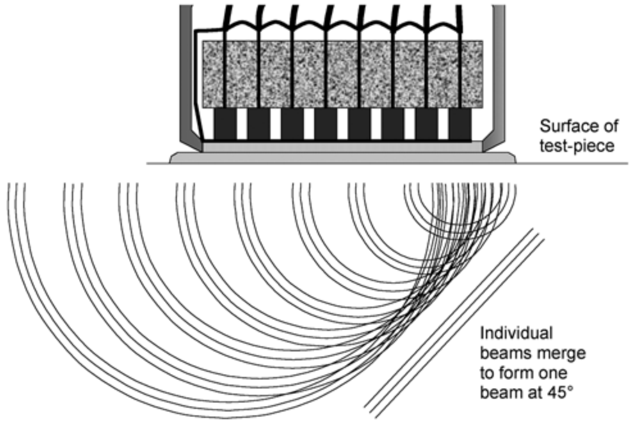

Figure 12.5(a). Diagram showing how a phased array can be made to produce a compression wave beam propagating at an angle such as 45°. Excitation of the farthest left element must take place first, then the next element, and so on until the farthest right element has been excited last

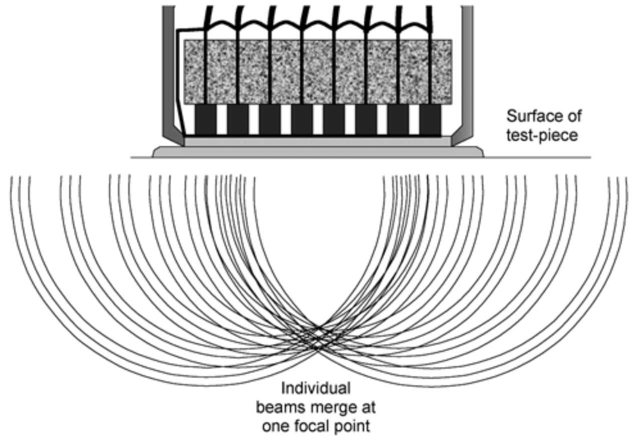

Figure 12.5(b). Diagram showing how a phased array can be used to produce a focused compression wave beam. As the position of the focal point is controlled electronically, it can be moved around without altering the physical structure or position of the array

Using Pythagoras's theorem, the distance from each array element to the focal point can be calculated as shown in the second column of Table 1. The time it takes for a compression wave beam to travel from the array element to the focal point can then be calculated, as shown in the third column, finally allowing the appropriate time differences to be calculated, as shown in the fourth column.

Table 1. Calculation of the focal law to focus a compression wave beam 10 mm below the example array

	Path length to focal point (mm)	Beam travel time one way (µs)	Relative time for array controller (ns)
Array element	$L_p = \sqrt{(D_{horizontal}^2 + D_{vertical}^2)}$	$t = L_p / v$	$\delta t = t - t_{minimum}$
1	**10.218** = $\sqrt{(2.1^2 + 10^2)}$	**1.732** = 10.218 / 5.9	**36** = 1732 – 1696
2	**10.111** = $\sqrt{(1.5^2 + 10^2)}$	**1.714** = 10.111 / 5.9	**18** = 1714 – 1696
3	**10.040** = $\sqrt{(0.9^2 + 10^2)}$	**1.702** = 10.040 / 5.9	**6** = 1702 – 1696
4	**10.004** = $\sqrt{(0.3^2 + 10^2)}$	**1.696** = 10.004 / 5.9	**0** = 1696 – 1696
5	**10.004** = $\sqrt{(0.3^2 + 10^2)}$	**1.696** = 10.004 / 5.9	**0** = 1696 – 1696
6	**10.040** = $\sqrt{(0.9^2 + 10^2)}$	**1.702** = 10.040 / 5.9	**6** = 1702 – 1696
7	**10.111** = $\sqrt{(1.5^2 + 10^2)}$	**1.714** = 10.111 / 5.9	**18** = 1714 – 1696
8	**10.218** = $\sqrt{(2.1^2 + 10^2)}$	**1.732** = 10.218 / 5.9	**36** = 1732 – 1696

By combining the type of calculation for beam steering with the calculation for focusing, it is possible to produce a focal law for any combination of focusing and steering, allowing the array to focus anywhere within the test-piece consistent with various limitations. These limitations include the length of the array, L, which affects the maximum distance at which focusing can be achieved; the centre-to-centre spacing of the elements, $\delta e_{c\text{-}c}$, which affects the generation of artefacts in the beam; and the frequency, f, which affects the penetration depth in the same way as for a conventional probe.

As an array controller must contain all the electronics for a separate digital pulser-receiver for each channel, it is much more expensive than a conventional single-channel pulser-receiver. In addition, it is vital to have software to calculate focal laws and to drive the array controller and this means that a PC must be built into the controller or a separate PC must be connected to it. This also adds to the cost. However, there is no need for a separate display or separate manual controls for each channel and as the electronics for all the channels are the same, the cost is not as high as might be expected. As a guide, a 32-channel array controller may cost approximately ten times as much as a single conventional pulser-receiver.

The two main physical components of an NDT system based on an ultrasonic array have now been described. The next section of this article briefly describes the way that results from an array system can be presented, comparing them with results from use of conventional probes.

Results from an array system

The results from a conventional probe in a single position are usually displayed as an A-scan (amplitude scan) which allows the NDT practitioner to see the amplitude of the signal as a function of time. As ultrasound usually travels at a fixed speed, this is equivalent to the amplitude as a function of distance in the test-piece. If the probe is moved in a straight line and A-scan data are recorded regularly, a B-scan (brightness scan) display can be obtained. This comprises multiple A-scans laid side-by-side usually with amplitude represented as colour or brightness. If the probe is moved in two dimensions then a top view of the test-piece can be displayed, with the maximum amplitude shown for each point over which the probe has been moved. This is called a C-scan. The final conventional way to present results is a D-scan, which is similar to a C-scan, but with the data taken at right angles to the C-scan.

An array system can produce A-, B-, C- and D-scans. However, less probe movement is required. An A-scan is produced by an array in a single position, but a B-scan can also be produced in this way. C- and D-scans can be produced by moving the array only in a straight line, whereas a conventional probe must be moved in two dimensions.

A different type of scan produced by an array is the S-scan (sector scan). This usually has a characteristic triangular shape as shown in Figure12.6. The array is taken to be at the top of the triangle, and the signal amplitude is shown with colour or brightness. An S-scan can be obtained from an array in almost any configuration including with beam focusing, beam steering, used with a wedge, in direct contact with the test-piece or with immersion testing. An *uncorrected* S-scan is like a B-scan but with the A-scans laid out in a sector. It therefore presents the data in the form in which they are recorded digitally. A *corrected* S-scan takes into account phenomena such as ultrasonic refraction which changes the angle of the beam as it propagates. It therefore shows actual positions of features in the test-piece such as flaws and surfaces.

The most important aspects of an ultrasonic array system for NDT have now been described. The next section outlines the main advantages and disadvantages of such a system.

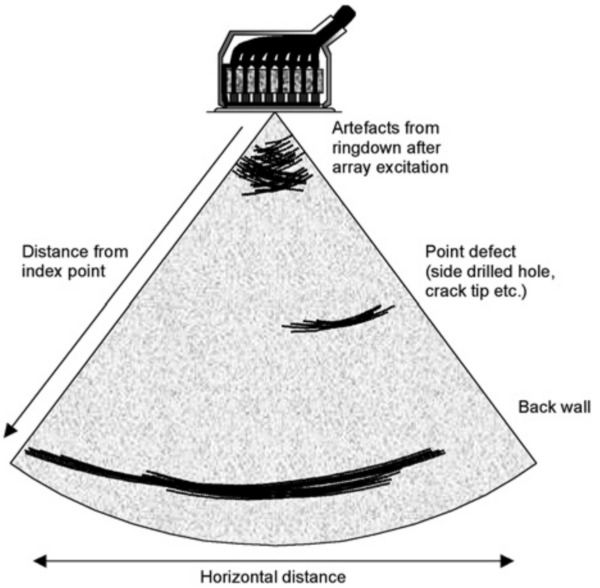

Figure 12.6. Schematic diagram of the S-scan, uniquely used to display results from a phased array. Other possible displays include the conventional A-scan, B-scan and C-scan

Advantages of an array system

An array system has several advantages. These include:

- ❑ At the simplest level, an array system can mimic many different conventional probes, reducing the need to stock multiple probes for different purposes.
- ❑ For simple configurations, the S-scan should provide a much more immediate and easily interpreted presentation of results than is possible with conventional probes.
- ❑ Sensitivity to defects can be maintained throughout the depth of a test-piece by using dynamic depth focusing in which a set of focal laws is used for different depths in a single inspection.
- ❑ The inherent accuracy of the locations of the elements in an array may allow better defect position measurement accuracy if the 'dB drop' method can be used without moving the array.
- ❑ Provided ultrasonic coupling can be maintained between the full surface of an array and the test-piece, full area coverage can be completed much more quickly with a suitable array than with a conventional probe.

- The flexibility of electronic configuration of an array means that it can be optimised for a particular inspection by the practitioner at point of use, potentially avoiding the need for a custom-manufactured conventional probe.
- It may be possible to complete a complex inspection with a single array configured in several different ways by the array controller rather than with several conventional probes.
- An array will often allow simplification of the mechanics of an automated scanning system, replacing physical movement with electronic control and hence enhancing the reliability of the system.

Disadvantages of an array system

Although an array system has several advantages, it also has several disadvantages, some fundamental and some which will be overcome as the technology and its use mature. These include:

- The complexity of an array leads to an inevitably higher cost than for a conventional probe. This may be offset by its flexibility in replacing several conventional probes, but physical damage to the array will lead to a greater one-off financial penalty.
- The complexity of an array means that reliability may be reduced. In relation to this, there is not yet a recognised and routine way to check that all array elements are working.
- The complexity of an array controller leads to an inevitably higher cost than for a conventional flaw detector. However, the price may be expected to reduce as sales accumulate, development costs are written off, and competition in supply increases.
- Conventional probes and their use are the subject of many years experience and development of standard procedures. Array systems lack this strong foundation in NDT practice.
- Exploiting the advantages of an array system demands relatively complex system setup and careful choice of many different possible configurations. This raises the skill level required by the NDT practitioner and increases the risk that a defect may be missed because of an incorrect choice.
- The beam generated by an array is likely to be more complex than that generated by the equivalent conventional probe. This can lead to problems where, for example, the beam from an array is steered away from the back wall, but the precise configuration of the beam leads to unexpected detection of the back wall.
- An array is likely to have a larger contact area than a conventional probe, leading to difficulties with acoustic coupling on rigid surfaces.

Conclusions

It has long been a question why ultrasonic arrays have been much less used in NDT than in biomedical imaging but the reasons are becoming increasingly clear. First, real-time imaging is less of an issue in NDT as the test-piece is static or so quickly moving in production that human monitoring is impossible. Second, there is much greater variation between NDT test-pieces than between human subjects. Together, these have restricted the market for arrays and instrumentation, leading to high prices, low volumes, and lack of development. Now, with the costs of array controller design and production falling and the ease of development of software with an accessible user interface, widespread use of arrays in NDT looks imminent. Hence, an understanding of the technology is becoming increasingly important for the practitioner.

The most important aspect of the ultrasonic array for the NDT practitioner to understand is that it may be viewed simply as a highly flexible probe which can be made to behave in the same way as many different conventional probes using the control capabilities of the electronic array controller and its software. Taking this approach, three main developments are needed. The first is to reduce the price of an array further so that it is similar to that of the probes it will be used to replace. The second development is to reduce the price and physical size of the array controller so that they match those of a flaw detector used with conventional probes. The third development is to improve the software so that an NDT practitioner requires as little additional training as possible to use the array.

Although an array and electronics can replace many different probes, this ignores the possibilities they open up to improve NDT beyond the capabilities of conventional systems. In the next article in this series, a number of variations on the theme of ultrasonic arrays for NDT will be considered to help the NDT practitioner and the NDT development engineer to appreciate what may be possible in future, so that new developments can be explored most effectively. These variations include curved arrays, arrays with more than one line of elements, and arrays operated in different ways, not just mimicking conventional probes, for example through the synthetic aperture focusing technique and the total focusing method.

References

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