Phased-Array Resolution Assessment Techniques

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Abstract:

This paper presents a review of the methods by which phased-array formed beams can be analysed for steering and resolution limitations. In-house methods have been developed by several users and an ASTM Standard Guide has also been produced that provides some options. However, the concepts of beam characterisations of phased-array generated pulses for NDT seem to require further discussion to avoid misuse.

Keywords: Phased array, resolution, ultrasonic, beam-steering

Introduction:

Phased-array applications in NDT have been on the rise for the past decade. The advent of the portable phased-array instrument accompanied with recent reductions in price has provided easy access to the technology. As with the previous single-channel ultrasonic instruments, phased-array ultrasonic units are digitally controlled and have a variety of menus requiring user input. But the menus provided by phased-array instruments generally require more input data. Both single channel and phased-array units provide pulser voltage and duration controls, A-scan range and delay controls, plus many other identical aspects. But some of the items in the phased-array units are unique to the technology. Until users become accustomed to the menu options they may forget to enter important parameters or, equally critical, they may enter values that are inappropriate.

Beam focusing and beam steering are the two main features that set the phased-array instruments apart from the traditional mono-element units. These features, along with the informative displays (B-scans C scans and S-scans) provide the user with the potential to produce projection images that greatly improve the options for interpretation and evaluation of indications.

However, in order to provide "useful" images the user should keep in mind the limitations of phased-array technology. But this also requires that they have a better understanding of the basic aspects of ultrasonic inspection principles.

Too often it is seen that a scan-plan has an operator configure the instrument with an angular sweep well beyond all practical limits (of both capabilities of the system and display parameters for interpretation). But even more disappointing is the failure of the operator to recognise the basic limits of ultrasound. After all, this is still just an application of ultrasonic testing and the principles taught at Level 1 still apply!

Varying the focus of the beam is a capability of the phased-array instrument not available to the mono-element units.

But when did the average ultrasonic technician ever "focus" a beam in normal weld inspections? Pipeline girthweld inspections using zonal discrimination are probably the only place in which a focused beam is used in the interrogation of the weld for flaws. Some esoteric sizing assessments might use a focused beam; but this is only after a flaw has been detected by another method.

Generally focusing in weld inspection is not the norm. In fact, most weld inspection codes assume that mono-element techniques are used and these are unfocused beams. It should be recalled that most pulse-echo weld inspections are done using some form of "distance amplitude correction". These are based on a basic beam divergence. Therefore, unless the application really requires the resolving advantage of a focused beam the focal law should be unfocused. For most probe apertures this can be accomplished by entering a very large value for the "focal distance"(the writer typically uses 500mm). The important aspect here is to enter a value at or greater than the natural focus (i.e. the near field distance for the equivalent flat monoelement probe). Even a large aperture of 500mm^2 at 5MHz in shear mode in steel will have a near zone of only about 250mm.
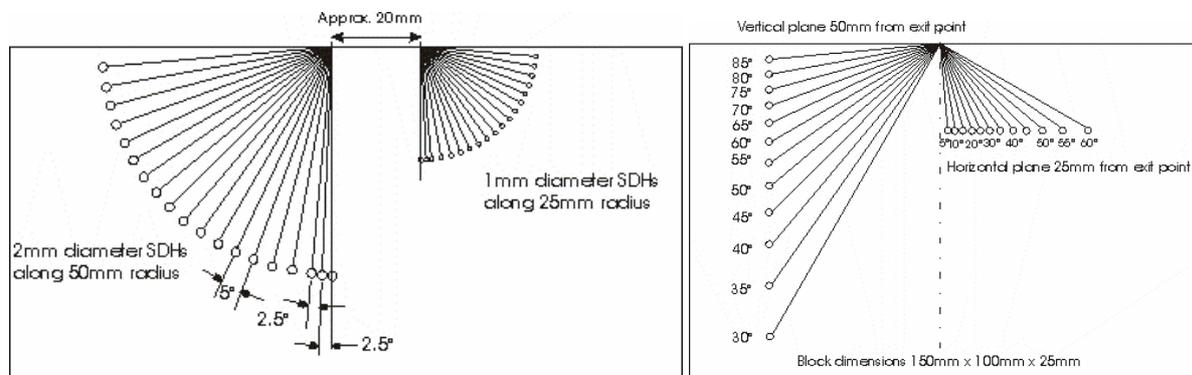
Beam steering limits are described in various sources [1,2,3]. This is generally a function of probe design (and to some extent instrument timing limitations). However, when beam steering is combined with focusing, some of the "generalities" made by these "rules of thumb" may be inadequate to define the limits. In fact, it may not be appropriate to consider the steering limits of a focused beam by the same methods used for an unfocused beam.

To assess the actual performance of a phased array system will require that the capability requirements are well defined and matched to the needs of the application. Unless there is a specific need for high resolution capabilities then there should not be a requirement to assess the spot size or temporal or angular resolution. However, if temporal and/or angular resolution is required it should be considered with the needs of the application in mind.

Steering and Focusing Assessments:

Several methods of performance assessment are described in ASTM E-2491[4]. Annex A2 describes a method of steering assessment using side drilled holes (SDH) arranged in the plane of focusing (to be determined by the user). But this option (see Figure 1) combines the focusing capabilities with the steering assessment.

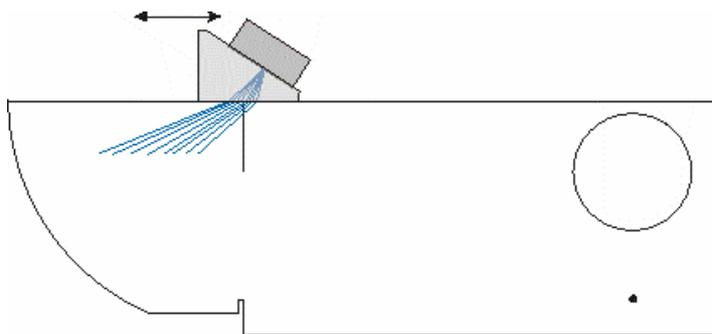**Figure 1   Example Targets for combined Steering and Resolution**

It is noted in the ASTM guide that corrections will be required to compensate for movement of the "apparent" exit point along the block entry surface. Therefore, in most cases, it will be necessary to compare only the adjacent responses from a peaked position because the full angular sweep of the used angles will not provide a peaked response for all targets due to the exit point movement.

ASTM E-2491 also makes provision for other options of steering assessment. An alternative assessment may use a single SDH at a specified depth or sound path distance. Displaying the A-scan for the maximum and minimum angles used would assess the steering capability by observing the S/N ratio at the peaked response. This assessment effectively measures the angular beam size at that target distance.

The hole patterns described in ASTM E-2491 are examples of the possible layouts that might be useful for a general assessment. But not all applications will use 25mm or 50mm half-path distances and 5° angular increments in a vertical plane 50mm from the exit point or in a 25mm deep horizontal plane. And obviously the small diameter closely-spaced holes will not be resolvable for low frequency pulses or in highly dispersive austenitic materials. Therefore, it may be necessary to configure custom targets for specific steering and resolving assessments. Instead of a specific angular separation of the targets the user may be more interested in a defined distance and various soundpaths or planes.

However, for the average weld inspection applications most operators would find it adequate to assess the beam steering based on the ability of the system to maintain a uniform amplitude over the angular sweep range. This is in effect what is done when performing angle corrected gain (ACG). This is often combined with the function of correcting for wedge delay. The operator simply directs the beam at a radiused surface (as in Figure 2) and software adjusts the receiver amplifiers for a uniform amplitude response from each of the focal laws in the angular sweep range. Since the soundpath to the radius target is a constant, this allows the software to calculate the total time and subtract the equivalent time in steel to obtain the time in the wedge and subtract that from the display. This provides the necessary correction to establish the steel to wedge interface time and thereby determine the zero-depth. for each focal law. Note; this is done on a focal law by focal law basis so each A-scan is corrected individually, thereby compensating for exit point differences.

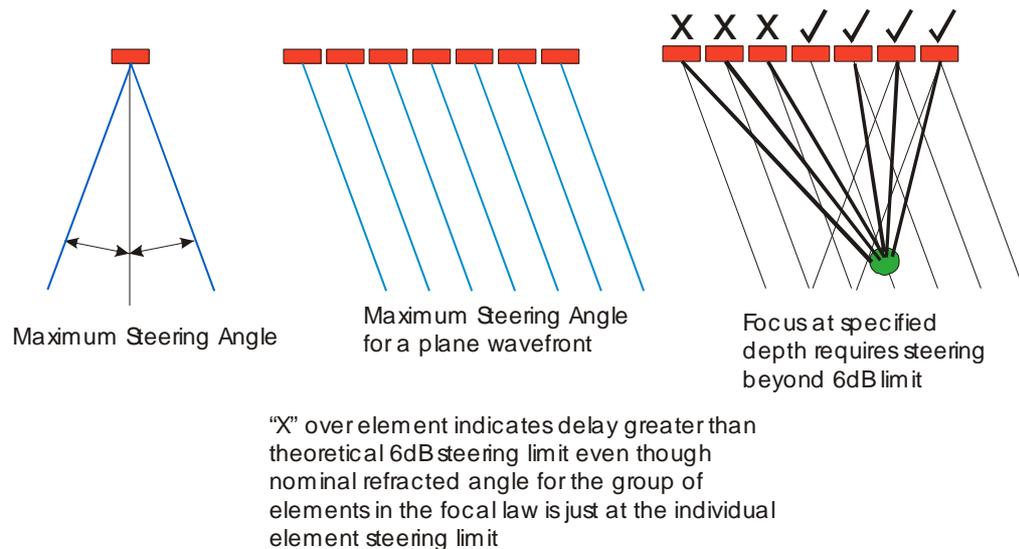**Figure 2   Establishing steering capability by ACG**

Establishing steering "capability" using the response of the infinite radius reflector is perhaps a bit coarse and relies heavily on the phased-array's amplification system to "compensate" for echo transmittance. However, even with this steering assessment it can be seen that there are limits to which the beam can be directed off its natural refracted angle and still maintain a constant response.

The "rule of thumb" that steering is limited to the 6dB angle of the individual elements is perhaps adequate for this coarse assessment using the radius from the V1 or V2 blocks. For the typical linear array probe this limit can be estimated. Fore example, a 5MHz linear array with a 0.6mm pitch mounted on a polystyrene refracting wedge would have a pulse-echo 6dB divergence angle of approximately 20°. On a 31° refracting wedge that would indicate that we might be able to steer from 11° to 51° incident angles and thereby reasonably achieve refracted angles from 15° to about 70°. If instead of the 6dB range (which uses the 0.44 constant for the pulse-echo value) the intent is to use the free-field equivalent for the transmit-only, then the constant changes to 0.32. This would reduce the useable steering range in the wedge to +/-14.5°. That would reduce the working refracted angles to about 23-63° in shear mode using the 31° refracting wedge.

Greater challenges are encountered when the application requires resolution as well as basic steering. In addition to simply redirecting the bulk wave the phase timing requires the wavelets to converge. This may mean more steering at the wavelet level than would be required for the basic steering. This is illustrated in Figure 3. Obviously this condition is most likely to occur when focusing is attempted at or near the maximum nominal steering angle.

Figure 3   Steering limits at the wavelet level

Maximum Steering Angle

Maximum Steering Angle for a plane wavefront

Focus at specified depth requires steering beyond 6dB limit

"X" over element indicates delay greater than theoretical 6dB steering limit even though nominal refracted angle for the group of elements in the focal law is just at the individual element steering limit

An application that specifies a resolution capability for a phased array pulse may result in reduced steering limits as assessed by one of the assessment options. This is further complicated by the fact that we may require temporal or angular resolution, or both. Hole patterns in Figure 1 are an effective and intuitive method of assessing resolving ability of the phased array configuration.

Focusing has the effect of concentrating sound pressure at a region. This tends to increase signal to noise ratio locally. But the wavefront is not limited to the 6dB drop region. The concept of the 6dB pulse-echo drop just indicates the dimensions off the central maximum where the pressure level is reduced to half the maximum.

An obvious application for angular resolution is detailed corrosion mapping. In this type of applications we want to not only identify the minimum wall thickness, but also assess the extent and shape of the corrosion. The horizontal plane of SDHs as indicated in Figure 1 not only allows assessment of angular resolution for S-scans, it could be used to provide an indication of how close two pits could be before they are blurred into a single source. The spacing of the targets incrementally decreases so a limit can be indicated by the traditional 6dB separation criterion; i.e. two peaks separated by a drop of 6dB or more constitutes 2 separate sources.

Practical Verification of Phased Array Steering and Resolving Limits

To provide a practical view of these guidelines we can use the performance results from a sample of probes and the recommended targets indicated in Figures 1 and 2. Three linear phased array probes were selected to compare the steering and resolving characteristics. The probes were;

- 2MHz 64 element with a 0.6mm pitch and 10mm passive aperture

- 5 MHz 64 element with a 0.6mm pitch and 10mm passive aperture

- 10 MHz 32 element with a 0.3mm pitch and 10mm passive aperture

The first two probes were mounted on a refracting wedge producing a natural refracted angle of 55° shear mode and the third probe on a refracting wedge producing a natural refracting angle of 60° shear mode.

Each was configured for a sectorial scan with an angular sweep range from 35° to 75° in 1° increments. The portable instrument was then calibrated on the IIW block to produce a constant arrival time from the 100mm radius for each focal law (time-base delay calibration) and the amplitude response from the 100mm radius was set to achieve 80% screen height for each focal law (angle corrected gain). These settings were pre-requisite for both the assessments done for the unfocussed conditions (focus in sound path set at 500mm) and for the assessment of the side drilled holes at 50mm sound path using a 50mm focal length for each angle of the focal laws.

Using these settings an S-scan was captured from the 100mm radius of the IIW block and the 50mm radius of side drilled holes and the performances reviewed. The blocks used were made of aluminium.
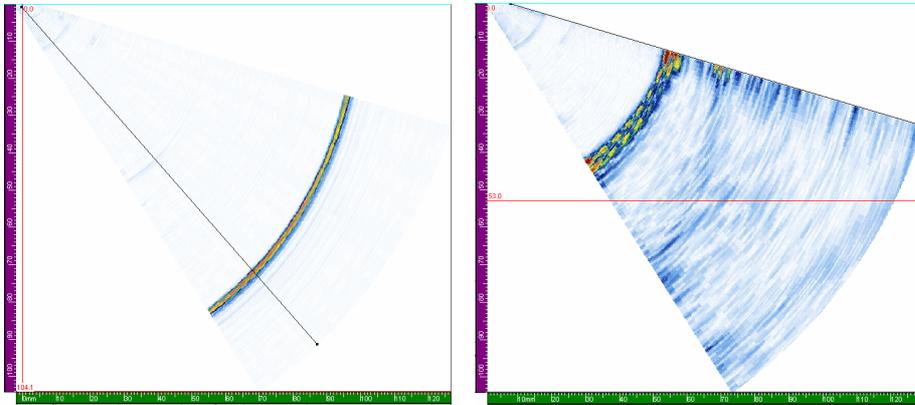
Observations

Data collected was in the form of S-scans with a fixed position on the IIW or Resolution block using the 50mm radius of side drilled holes. This results in a drift of the exit point forward with increasing angle. As a result, the responses from the side drilled holes may have their maximums at angles indicated on the S-scan at other than the actual angle of refraction. A similar effect is seen for the response from the 100mm radius of the IIW block. The maximum response from the radius of the IIW block is seen to be relatively uniform for the 2L64 probe where a larger beam divergence reduces the directivity effects of the reflection off the radius. The 5L64 and 10L32 probes show a notable deviation from the uniformity of response across all angles.

Figures 4 through 9 illustrate the S-scans for the 3 probes on the 2 sets of targets for the unfocused and focused at 50mm sound path conditions. Effects of focusing improving the resolution are clearly evident. The lack of resolution in the near fields can be seen for the 5L64 and 10L32 probes when the S-scans of the side drilled holes are viewed.

The S-scan plots do not easily convey the relative amplitudes. This is accomplished by plotting the amplitude responses from the targets with respect to the angles of refraction. As noted above, due to the relative exit point drift with varying time of each focal law sound path in the wedge, the actual angle made from the point of beam exit to the side drilled hole is not necessarily the same as the refracted beam indicated on the S-scan. The sweep range is from 35° to 75° and therefore ideally would indicate nine peak amplitudes starting and ending on a maximum. In fact in all three cases the S-scans indicate less than nine peaks. The differences are mainly in the amplitude drops between adjacent peaks. The amplitudes plotted against the refracted angles are seen in Figures 11 through 13.
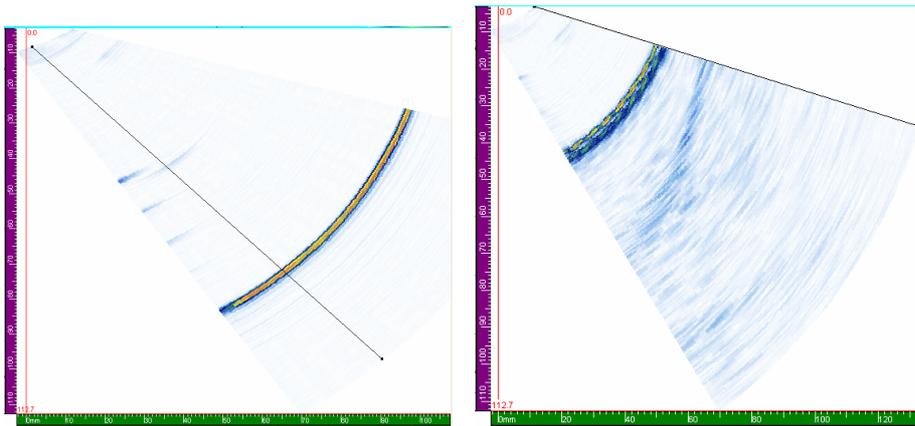
2L64 Probe

Figure 4   2L64_100mm radius unfocused

2L64 Unfocused with ACG on 100mm IIW   2L64 Unfocused on SDHs at 50mm

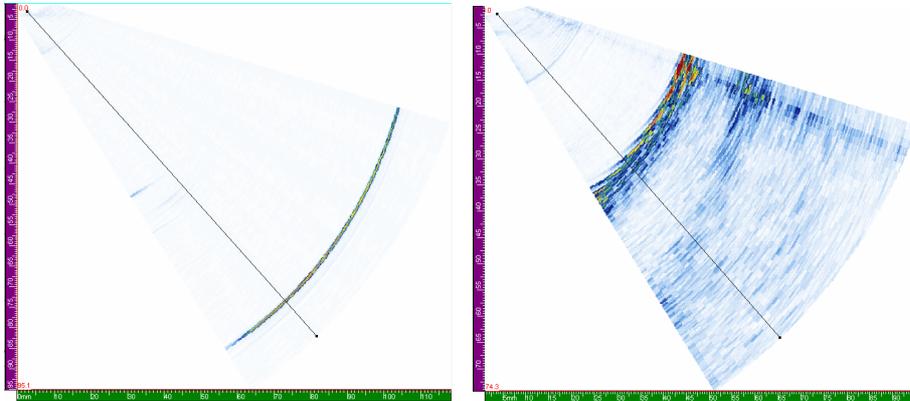**Figure 5   2L64_50mm SDH radius focused**

50mm FL with ACG on IIW   50mm FL on SDHs at 50mm

For the 2L64 probe the plot of amplitude versus angle indicates that not even at a dedicated focus of 50mm can the holes at 5° separation can be resolved to the 6dB level. Large amplitude responses at the extremes of the sweep range indicate the large gains added by the system in the ACG (angle corrected gain) to compensate for echo transmittance.

5L64 Probe

Figure 6   5L64_100mm radius unfocused

5L64 Unfocused with ACG on 100mm IIW   5L64 Unfocused on SDHs at 50mm

Note that for the SDHs at 50mm using this focal law the SDHs occur in the near field so amplitudes are expected to be irregular.

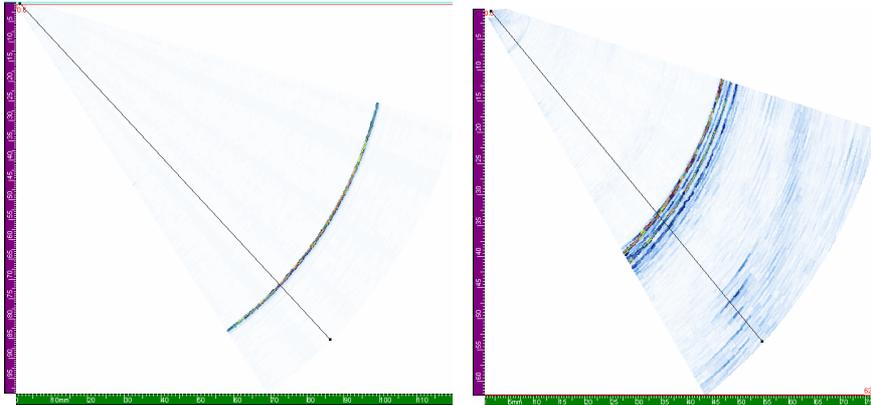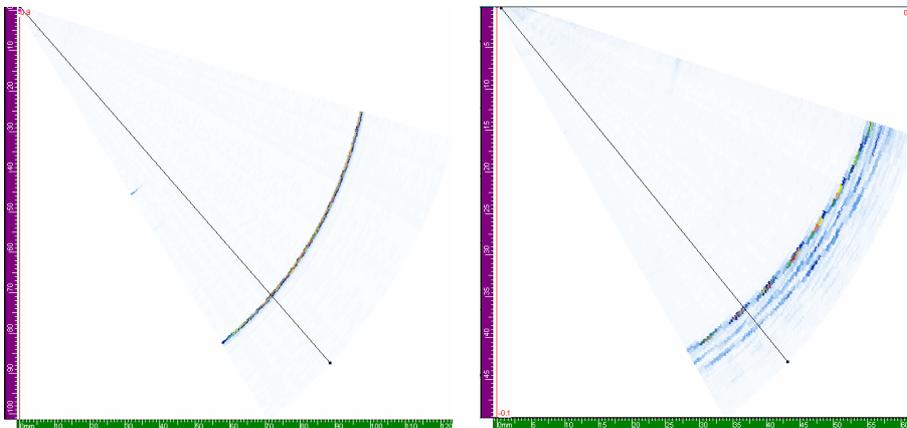**Figure 7   5L64_50mm SDH radius focused**

50mm FL with ACG on IIW   50mm FL on SDHs at 50mm

10L32 Probe

Figure 8   **10L32_100mm radius unfocused**

10L32 Unfocused with ACG on 100mm IIW   10L32 Unfocused on SDHs at 50mm

Note that for the SDHs at 50mm using this focal law the SDHs occur in the near field so amplitudes are expected to be irregular.

Figure 9   **10L32_50mm SDH radius focused**

50mm FL with ACG on IIW   50mm FL on SDHs at 50mm

When using a focused beam the holes are well resolved with the 10L32 probe.

Overlaying the hole pattern and probe position with the S-scan display for the 10L32 probe as in Figure 10 illustrates the effect of exit point drift. Although the holes can be seen to be well resolved, the depths but not the actual angle to the targets match reasonably well. The peak signal is indicated for the hole seen at 55° and the hole at 35° is apparently not detected in the S-scan and the hole at 75° is weakly detected as a result of the off-axis incidence. Wedge path travelled, angles used, attenuation of the test materials as well as the aperture size and optical focusing factor are some of the factors that will have a bearing on the resolution and exit point drift.

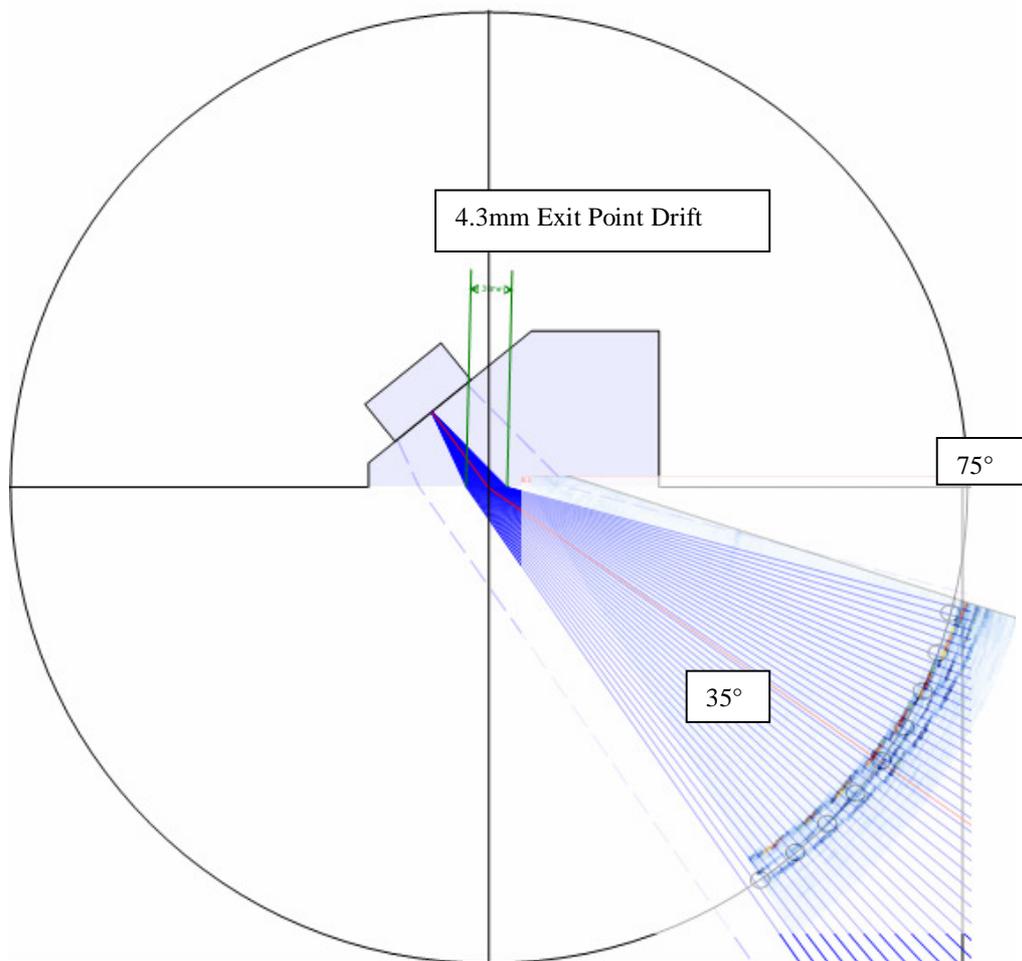**Figure 10   10L32 focused S-scan display as overlay on modeled probe and SHDs**
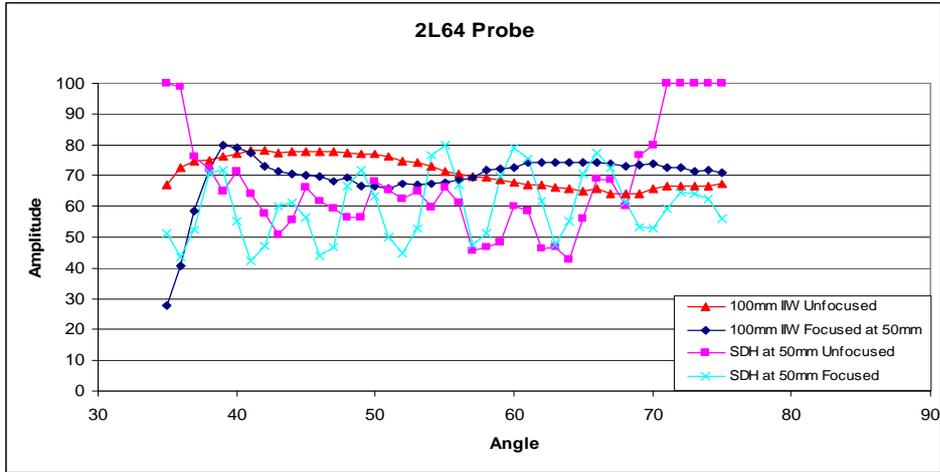
Figure 11   2L64 Relative Amplitude Plots

Figure 12   5L64 Relative Amplitude Plots
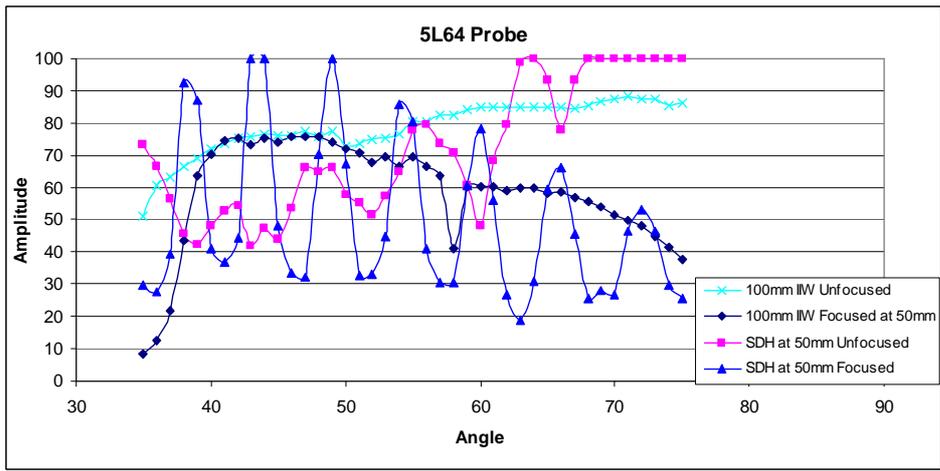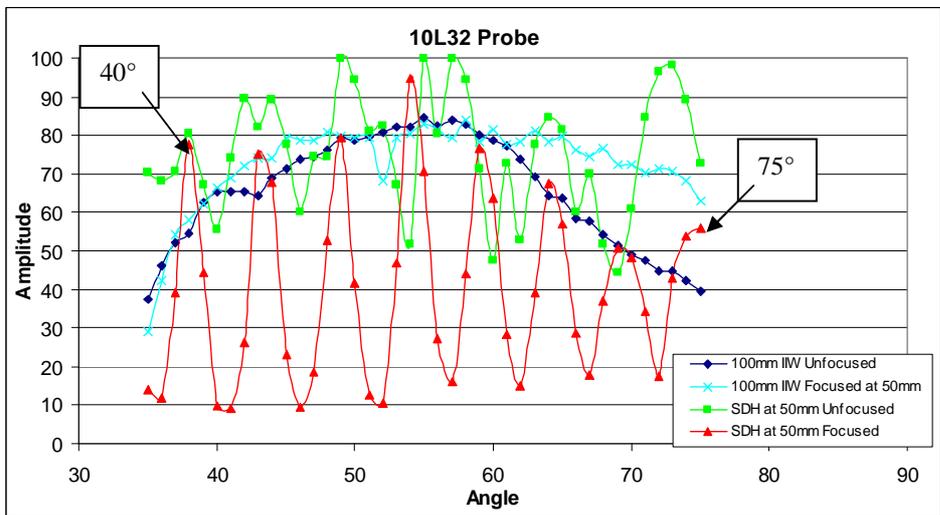

Figure 13   10L32 Relative Amplitude Plots

Comments on Angle Corrected Gain

Angle corrected gain (ACG) is intended to be a means of compensating for the pressure variations that result from echo-transmittance differences for different angles. Krautkramer[5] instructs that the important aspect determining available sound pressure in pulse-echo testing is the transmitted pressure in round-trip of the pulse. This is obtained by multiplying the transmittance in the send-path by the transmittance in the return path. The product is the "echo-transmittance' and the graph from Krautkramer (Diagram 7 in the Appendix of the third English edition) for a Perspex-steel interface is shown in Figure 14.

Figure 14   Echo-transmittance for Perspex-steel interface (from Krautkramer)
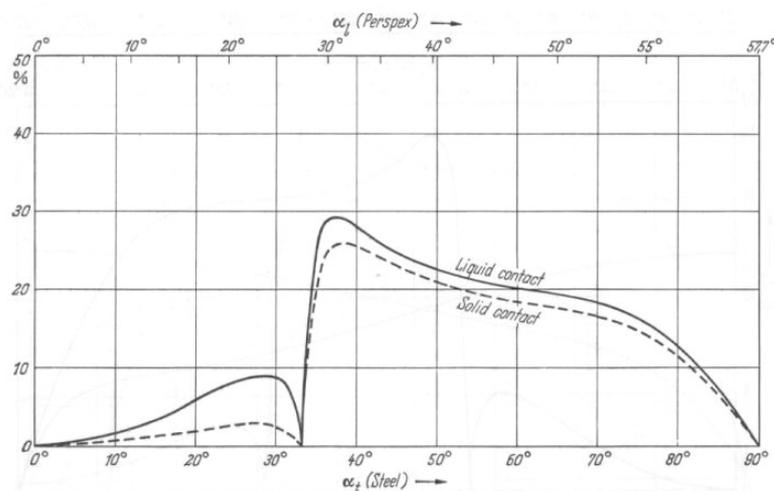

Figure 14 would suggest that in the range of 35°-75° there is a gradual drop in available pressure from about 30% to 15% or about 6dB. Ideally the phased array instrument would apply ACG by adding small increments of amplification to the summation amplifiers for each focal law of increasing refracted angle. Moving the probe back and forth across the IIW midpoint of the 100mm radius as in Figure 2 provides each focal law the path to produce the maximum response from the radius. Without the ACG the amplitude response would trace out a profile similar to the curve in Figure 14. A small correction is also be required to compensate for the attenuation differences with small path differences of each focal law in the wedge material. But this compensation is small considering most wedge plastics have attenuations of about 0.1-0.2dB/mm and typically less than about 2-3mm of path difference might exist for the range of focal laws in a wedge.

However, other factors may affect the compensation applied for ACG and may result in gross over-compensations if not considered judiciously. The main factors are the beam size and the design of block used for ACG.

The process of amplitude compensation from a target is best done using the portion of the beam in the far field. However, the concept of ACG becomes problematic if using a focused beam. This is further complicated by the fact that the focal plane may not be a fixed distance (like the radius) so other methods of compensation may be required.

For unfocused beams, beam divergence will provide a directivity dependence. By this we mean smaller divergences (higher frequencies and larger apertures) will be more sensitive to the integrating effect of the radius. The effect of this is seen when the operator attempts to use an inappropriate angular sweep range with the IIW block. The standard IIW block illustrated in Figure 2 can be seen to have less than 90° of 100mm radius. In fact, the line connecting the centre of the radius to the lowermost point having 100mm radius is 25° from the vertical. Another factor to consider is the near-surface limit. The curves in Figure 14 illustrate the effect of echo-transmittance up to 90° refracted angle. But these curves are based on mathematic equations and assume the ideal "ray" of sound without considering the fact that the real situation is a divergent pulse having a range of angles.
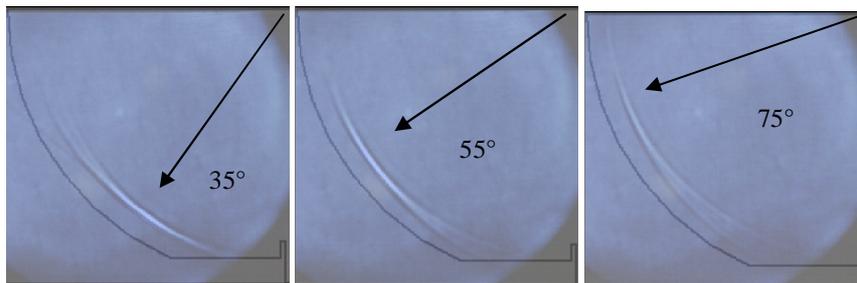
For angles less than the first critical angle the curve in Figure 14 illustrates that the available pressure returned is significantly lower than for above the first critical angle and this drops to zero at the critical angle.

With these three factors in mind, i.e. the 25° lower limit of the standard IIW block, the incompatibility of the ideal echo-transmittance curve with the reality of a divergent beam, and the effects of the critical angle threshold; we can soon recognise the practical limits to ACG.

At the lower angles beam divergence will mean that portions of the beam less than about 25° will be directed away from the probe. At the higher angles (e.g. >70°), beam divergence will provide losses of portions of the beam to internal reflections in the wedge and mode conversion to Rayleigh waves. Both situations will result in portions of the off-axis beam being lost (unavailable to return to the probe). Add to this the significant reduction in echo-transmittance at and below the first critical angle and it can be seen that the practical range for angular compensation limits the useful range of the sectorial scan in shear mode.

The practical range of ACG using the standard IIW block is therefore approximately 40°-70°. For some configurations where a narrow unfocused beam can be made, this might be extended to 35° to 75° (but 35° is extremely close to the critical angle). Figure 15 uses photoelastic visualisation to illustrate the actual beam divergence of a phased array generated pulse for 35°, 55° and 75° refracted angles. These are overlaid on the IIW block outline and illustrate how the off-axis portions of the beam in the 35° and 75° refracted positions are lost due to redirection at the 35° condition and echo-transmittance for the upper angles of divergence by the 75° condition (note the weaker intensity of the pulse above the 75° line indicating that the pulse is quickly fading away in the image).

Figure 15   Off-axis effects in the IIW Block hinder ACG

As a result of these losses, the receiver amplifiers may add significantly more gain than would be predicted by the basic echo-transmittance calculations in order to balance the echo amplitude for ACG

Conclusion

Standard weld inspections assume unfocused beams. DAC or TCG constructions and AVG sizing techniques are based on normal divergence of the unfocused beam. Therefore focusing in standard weld inspections is not generally acceptable.

For the few applications in which focusing is required, the operator must be aware of the limitations of the beam formed by the phased-array system. This includes:

- Probe design
- Instrument timing limits for phasing
- Plane of required focusing
- Near-zone extents of the beam (with provision for wedge delay effects)
- Beam size required to improve signal-to-noise ratio and resolution
- Required resolution and the method of assessing that resolution

Only when the requirements of the application are established can a method of assessment be assigned. Custom assessment blocks may be required for special applications. Work is being carried out to establish phased-array beam characterisation blocks that can provide multiple functions in this regard (ASTM E-2194 provides some examples).

Ultimately the operator must be better aware of the limitations of any phased-array system and design the technique with the limitations and any necessary performance demonstrations in mind.

Acknowledgements

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