Photoelastic Visualisation _ Phased Array Sound Fields
Part 21 – Phased array static angle with wedge – 45° focussed at 20mm half-path

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The video to this article can be seen here: www.ndt.net/search/docs.php3?id=17601&content=1

1. Introduction

This technical note is Part 21 of a series in NDT.net.

Generally weld inspection by ultrasonic testing is done with angled transverse wave using an unfocussed beam. Some applications however, require that the beam size be reduced to just an area of interest. This would require beam focussing. A good example of weld inspections using focussed beams is the technique called zonal discrimination. In early days of the technique an array of internally focussed probes were used (or even earlier were probes using lenses made of two different velocities of plastics). Multiple probes were mounted in individual holders with the beam from each probe directed with its intended focal point at a specific zone in the weld. Alignment of the beams at their specific targets was a tedious process.

A particular advantage of phased-array systems is their ability to focus a beam. As a result, phased-array systems have become popular in applications using zonal discrimination. But focussing can also be used to improve resolution of closely spaced flaws, increase amplitude response from small targets and increase tip diffraction signal strength to improve sizing estimates.

The point where focussing occurs, is limited to a point less than the near zone. Therefore, in order to take advantage of a focussed beam, one should have a fore-knowledge of the near zone length. This has been the topic of other discussions [1]. It is important to note that the near field can be extended in a phased-array system by increasing the aperture used and the actual near field distance is reduced as the angle of refraction increases.

Some operators have had difficulties with the concept of focussing as it seems to vary with phased-array system software. Simple versions of software allow no operator input and simply define a single focussing plane (depth) whereas other software permits the operator to select the plane. Figure 1 illustrates the general options that could be selected as the focal plane. Of course it would also be feasible to define angled planes other than just the True Depth and Projection (vertical) planes.
Because of the way phased-array software has been presented, many operators seem to have assumed that focussing a phased-array beam is essential. Few (if any) software packages actually have a default setting where there is no focussing so the operators sees a field that is to be filled called “Focal Distance” and expects that a number is to be entered. There are even training schools that actually instruct that weld inspection should be carried out with a focal distance entered that is 1.5 times the weld thickness, without regard for the effect of focussing on the test results and without regard for the ability to actually focus at that distance.

To illustrate the process and limitations of phased-array focussing, the photoelastic video uses a simple beam configured on a typical refracting wedge. The formation of the beam by the element-firing delays is analysed and the resulting pressure distribution examined with the photoelastic tools used throughout this series.

2. Configuration of the probe and delay laws

The focussed beam is imaged in the glass specimen containing several targets including a 5mm diameter through hole. Because its size and depth are known, the hole is maintained in the video image to allow distances to be scaled.

Figure 2 illustrates the probe placement on the glass specimen with a line indicating the intended path of the centre ray, its refracted angle and the intended position of focussing.
The delay law selected uses 16 elements starting at element #14. This provides a typical mid-range travel in the wedge material. Dimension markers in Figure 2 indicate the intended refraction angle and the intended point of focus which was configured to be 20mm along the soundpath (termed the half-path in the software being used).

Civa modelling provides a good illustration of the timing delays applied to the active elements. These are seen in Figure 3.

Timing of the delays becomes far more complicated when a wedge is used compared to the situation where we have direct contact to the test surface. Delays are calculated based on an optimisation using the centre ray from the midpoint of the active aperture following a path that is based on the middle ray refracting at the defined angle.
If we assume that the centre of the beam follows the intended 45° refracted angle beam path, we can extrapolate a line back to the centre point of the aperture starting at the intended focal point and determine the incident angle for that beam. This provides us two known distances in the two media (the wedge material and the test piece material).

Steering and focussing through a planar interface is described by Schmerr [3]. Travel times to the focal point are calculated based on the central ray from the aperture and then determining the separate travel times for a series of rays extrapolated from the focal point in the test piece to the wedge/specimen interface. Using a Cartesian coordinate system with a fixed reference point, Snell’s Law is then used to extrapolate rays back to the plane on which the elements lie (i.e. 36° in the case of our example). For each ray used, the intersection points of the rays reaching the element plane in the wedge are determined by solving the equation for the intersection of lines. The general conditions for our example are indicated in Figure 4 where only 2 outlying rays are used. Note that for the general equation, the rays in the wedge drawn from the points of intersection at the specimen/wedge interface need not intersect at the active aperture. Instead, the intersection points on the element plane are used to derive the general equation for all points that will provide incident angles that produce refracted rays to the focal point.

![Figure 4](image_url)

**Figure 4** Representation of rays to calculate delays to a focal point in specimen

Having determined the ray paths for each ray in both the wedge and glass, the time in each medium is calculated by dividing the ray path distance in each medium by the acoustic velocity in the medium. Adding the time of the ray in the wedge to the time of the ray in the glass gives the total transit time to the focal point from a point on the element plane.

Plotting the “X” coordinate for each point on the element plane against the total travel time produces a curve with the approximate shape defined by a quadratic equation; i.e. 

\[ t_x = ax^2 + bx + c \]

where \( t_x \) is the total travel time, \( x \) is the distance of the line intersections with the wedge/array interface and \( a, b, \) and \( c \) are constants.
We then have an equation that we can use to apply the X coordinate of each of our elements to derive the delays required for the element firing. The delays are derived from the total travel time of the beam from each element to the selected focal point. By comparing the calculated total travel we can calculate the delays. The element with the longest travel time should be fired first and the firing time of the rest of elements should be calculated relative to this element (delay times) by deducting the travel time associated to their beams from the longest travel time.

For our example with the 64 element probe on the 36° refracting wedge the calculated delays are as indicated in Table 1.

**Table 1  Delays for focussing at 20mm soundpath in Glass at 45°**

<table>
<thead>
<tr>
<th>Element</th>
<th>14</th>
<th>15</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
<th>29</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay (ns)</td>
<td>509</td>
<td>490</td>
<td>469</td>
<td>447</td>
<td>422</td>
<td>395</td>
<td>366</td>
<td>335</td>
<td>301</td>
<td>266</td>
<td>227</td>
<td>187</td>
<td>144</td>
<td>98</td>
<td>50</td>
<td>0</td>
</tr>
</tbody>
</table>

Wedge material Polystyrene
Start element 14
Velocity in wedge 2330 m/s
Velocity in Glass 3450 m/s
Element 1 elevation 11 mm

Delay time versus element is plotted in Figure 5.

**Figure 5  Plot of delay times applied to active elements**

Of some concern to those that require focussing, is the limits of an aperture to allow focussing. It is well understood that the maximum distance that a beam can be focussed is its near field distance (or natural focal length). This is the distance that the last maximum pressure is seen along the beam central axis when no focussing is applied. It has been described [1] how the wedge path and increasing refracted angle reduces the near field distance. Phased-array systems manufacturers may incorporate software to assist in
estimating the near field so that users can determine if the wedge path and aperture are adequate for focussing.

For the conditions used software suggests that the focussing required (at 20mm sound path) is just beyond the near field distance. The requested focal point and estimated near field distance are illustrated in Figure 6.

![Diagram showing near field and focal distance](image)

**Figure 6**  Empirical estimate of near field and 20mm focal distance

It was determined that most of the software calculations that are used to predict the near field reduction due to refracted angles, use empirical equations that merely estimate the approximate locations of near fields. More accurate results are had using software that uses full beam computations, such as Civa.

Three Civa simulations were run to assess the 45° beam produced by the 16 element aperture on the 36° refracting wedge. The elements had a passive aperture of 10mm and the delay law started with element #14. In the first simulation, no focussing was applied and the effects of attenuation were ignored. This indicated that the near zone would extend approximately 29mm into the glass. The cross sectional view and the pressure plot along the centre axis is indicated for this theoretical condition in Figure 7.
Figure 7  Civa simulation of unfocussed beam from 16 element aperture on refracting wedge indicates near field at 29mm path in specimen

When the delays applied in Table 1 are used, the Civa simulation predicts excellent focussing at the requested 20mm sound path. The simulated focussed beam is illustrated in Figure 8.
Figure 8  
Civa simulation of focussed beam from 16 element aperture on refracting wedge (no allowance for attenuation) indicates 20mm sound path in specimen

When the analysis of the frames from the video associated with this paper was made it was determined that the peak amplitude did not occur at 20mm sound path. To explain the discrepancy, more realistic conditions had to be used in the simulation. The waveform used for the simulation was a pulse centred at 5MHz with 80% bandwidth. It is well understood that a pulse with bandwidth passing through a material is attenuated and generally higher frequencies are attenuated more than lower frequencies. Since the near field distance is a function of wavelength, the effects of frequency-dependent attenuation will therefore have the effect of reducing the actual near field distance. Civa modelling was re-done on the computation for the focussed beam but this time taking into account the effects of attenuation in the wedge and glass. The results on the location of the near field peak are indicated in Figure 9.
Figure 9 Civa simulation of focussed beam from 16 element aperture on refracting wedge with compensation for attenuation indicates 16mm sound path in specimen.

Figure 9 indicates that the intended focal distance is reduced and occurs at 16mm.

3. Comments on the Video

The video begins with the beam for the 45° refracted angle imaged in the wedge. A graphic overlay indicates the intended refracted angle and the intended point of focus at 20mm sound path in the glass. This is illustrated here in Figure 9. The arced shape of the incident pulse is not well defined in the wedge; however, upon entry into the glass the arc shape can be seen to produce noticeable compression modes in the glass.
Figure 9  Incident compression mode and intended refraction angle and focal distance in glass.

Just prior to the focal point the wavefront is seen to have a slightly concave shape just as it is in the wedge. At the distance where the focal point is configured the concave shape of the advancing pulse flattens and after the focal point the beam takes on a convex shape. These are illustrated in Figure 10.
Using the stacking of frames as described by Schmitte [2] we can generate an image that accumulates the peak brightness at each frame. Placing the accumulated image over the probe layout we can see how it provides indication of the actual focal point of the beam. This is done in Figure 10.
Software used with the photoelastic system, Image Intensity Analysis software (IIA), allows rendering of image intensities. Using the rendering feature and rotating the image allows us to see the actual peak location of the pressure along the beam. This is done in Figure 11. The ruler in the video and the hole in the glass were used to correctly scale the dimensions tool and the peak is indicated at approximately 16mm. This is exactly where Civa predicted the focal location that would result due to the effects of wedge and glass attenuation.
4. Acknowledgement

During the development of this paper we were very fortunate to have Dr. Mohammad Marvasti provide assistance to explain in great detail, the process of delay law calculations using the Fermat principle.

5. References


For more information about the photoelastic system see http://eclipsescientific.com/Products/Training/Photoelastic/index.html
For information on the Image Intensity Analysis software see http://eclipsescientific.com/Software/IIA/info.html
The video to this article can be seen here: www.ndt.net/search/docs.php3?id=17601&content=1