Validation of aspects of BeamTool

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Abstract
Civa is a well known analytical software programme that has been extensively validated by field demonstrations. BeamTool is a much simpler software programme that has features that are useful for technique development and preparing images suitable to use in the preparation of scan plans that are now required in ultrasonic testing procedures. This paper provides an indication of the how close the traditional equations for several of the parameters calculated in BeamTool are as compared to the more accurate methods used in Civa. The features validated include near-field distance, beam divergence and refracted angles for both round and rectangular shaped elements.

Comparison of the values obtained by BeamTool, to those obtained from Civa, are displayed using graphical overlays. The comparison indicates that the results obtained by the traditional simple equations in BeamTool are reasonably close to those derived using the analytical methods.

Keywords: Modelling, validation, ultrasound, Civa

1. Introduction

BeamTool has become a popular software tool to simplify many aspects of building ultrasonic testing (UT) techniques and obtaining a quick understanding of the effects of altering the basic parameters. Many of the basic equations learned in UT training are incorporated into BeamTool and are used to generate raytrace images of the sound beam generated by the probe.

With the advent of phased array UT (PAUT) the computer assisted design (CAD) aspects of BeamTool have proven useful to avoid the complexities of locating the paths of emitted beam(s) when the active aperture size and start element and delays (angles) are varied. Further considerations are made in PAUT applications when focusing is being considered. Focusing can only occur at a distance less than the near field length for the unfocused beam. Therefore some estimate of the natural focal length (near zone) is required for focused beams to be effective.

Beam coverage can be assessed via the beam divergence and beam divergence is especially relevant to time of flight diffraction (TOFD) techniques.

Very detailed and accurate representations of the acoustic field in solids can be derived using finite element methods. However, the numerical solutions to determine the acoustic field can be very time consuming and the software for such precision is generally costly. Analytical software such as Civa [1] and UTSIM [2] provide extra detail such as A-scan response of a 3D beam in a solid. These programmes are indeed capable of faster computations than the finite element options; however, they are still somewhat time consuming and can require extensive training to learn all the features. BeamTool allows the user to create images and place probes on the modelled test piece and immediately see the paths of the beams and volume coverage. Although the representation provided by the ray-tracing methods may not be as accurate as finite element representations, they are generally considered adequate for the purposes of technique development.

In order that the user be confident that the representation on the model be close to the real situation requires validation (also called demonstration). In order to "validate" BeamTool, it was decided to compare the results obtained to those modelled by Civa. Civa has had extensive tests run in the lab in the CEA and these are reported in the annual Benchmark reports from the QNDE conferences [3]. The purpose of the benchmark study is to compare simulation results predicted by models developed and/or used by member centres and to see how well the predictions match the physical results.

2. BeamTool Validation Process

BeamTool uses many of the fundamental equations typically associated with UT. These equations are often approximations that are used as a "rough guide" to assist practitioners to estimate parameters in the test system. One of the common assumptions made in UT relate to equations that contain a wavelength value. Clearly this slants the results to a specific value even though this cannot be possible in a probe pulse that contains bandwidth. For example, a focal "spot" is in fact a focal region since many frequencies (wavelengths) are generated in a pulse.

This paper will consider how well the common equations used by BeamTool approximate;
- refracted angles
- beam divergence
- near-field distance,

These will be assessed for both round and rectangular shaped elements.
Since the computation considerations in Civa include bandwidth and material properties, and the Benchmark tests have indicated that the values predicted by Civa are close to those measured by systems having the same characteristic parameters, it is assumed that the Civa values may represent "truth" values. Therefore, the process of validation of the BeamTool will involved comparing the BeamTool value to the predicted Civa value for a given set of system parameters.

The resulting Civa plot of a beam can be overlaid in the BeamTool image. By ensuring that the relevant dimensions are maintained, the measurement tools in BeamTool are used to identify the pertinent values and quantify the differences.

2.1 Refracted Angle
Refracted angle is an assumed path of the centre of the beam based on the incident angle and ratio of acoustic velocities either side of an interface of two media. The angles are determined by the familiar Snell's Law.

$$ sin\,\theta_i = \frac{v_i\,sin\,\theta_r}{v_r} $$

where v_i and v_r are the acoustic velocities in the incident and refracting media and θ_i and θ_r are the incident and refracted angles.

2.2 Beam Divergence

Beam divergence is a characteristic of a wavefront passing through an aperture whereby the effect of diffraction causes the region at the edges of the aperture to bend. The amount of bending is a function of the aperture size and the wavelength of the pulse.

For a circular probe, the half angle of divergence is calculated from:

$$\sin\gamma = k\frac{\lambda}{D}$$

Where;
γ: Half angle of divergence
k: Constant for the -6dB envelope, $k = 0.51$ for circular element-transducers in pulse-echo
λ: Wavelength

For the rectangular probe, the half angles are derived from the size of the relevant side and wavelength as follows:

$$\sin\gamma = k\frac{\lambda}{L}$$

$$\sin\gamma = k\frac{\lambda}{W}$$

Where;
L: The long dimension of the rectangular probe
W: The short dimension of the rectangular probe
k: Constant for the -6dB envelope, $k = 0.44$ for rectangular element-transducers in pulse-echo

The term is relevant only in the far field of the beam.

2.3 Near-field Distance

Calculation of a beam's near-field is intended to identify the last peak amplitude along the beam centreline before a continuous pressure drop is seen along the beam axis. For the circular elements we can approximate the distance by considering the element diameter using a simple equation:

$$N = \frac{D^2 f}{4v} \qquad\qquad \text{OR} \qquad\qquad N = \frac{D^2}{4\lambda}$$

Where;
N: Near Field Distance D: Element Diameter
f: Frequency v: Material Sound Velocity
λ: Wavelength $\lambda = \frac{v}{f}$

Using these equations, the concepts in the EN 12668 [4] document can be used to derive the near zone length by re-arranging the parameters and applying the correction factor in the curve seen in Figure 1 for rectangular elements.

Effectively, the larger dimensioned side gradually dominates the near field length; thus the equation used for a circular probe, with a diameter of the larger dimension on the rectangle, can again be used for estimating the extent of the near zone. The near zone can now be determined by the equation;

$$N_{\text{rectangular}} = \frac{k_a (L^2) f}{4v}$$

Where;

k_a is a correction factor obtained from the curve in Figure 1,
L: The long dimension of the rectangular probe**Error! Bookmark not defined.**
f: Probe nominal frequency
v: Velocity of sound in the test piece

The short dimension of the rectangular probe (W) is not used directly in the equation, but is instead used to determine the aspect ratio required for the determination of the k_a value.
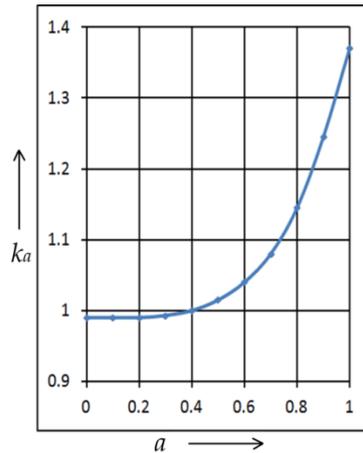
Figure 1   Correction factor applied to rectangular element near field calculation

Note: some references indicate calculation of the "effective near field length". This is not an actual length but is instead calculated based on the estimate of the "effective aperture". This value would normally be used in a beam assessment to work backwards from divergence angles derived from EMAT or SDH measurements as described in the standard for probe characterisations EN12668.

3. Observations
Velocity parameters for the simulations used the following values:
    Steel Acoustic velocity compression mode 5900m/s
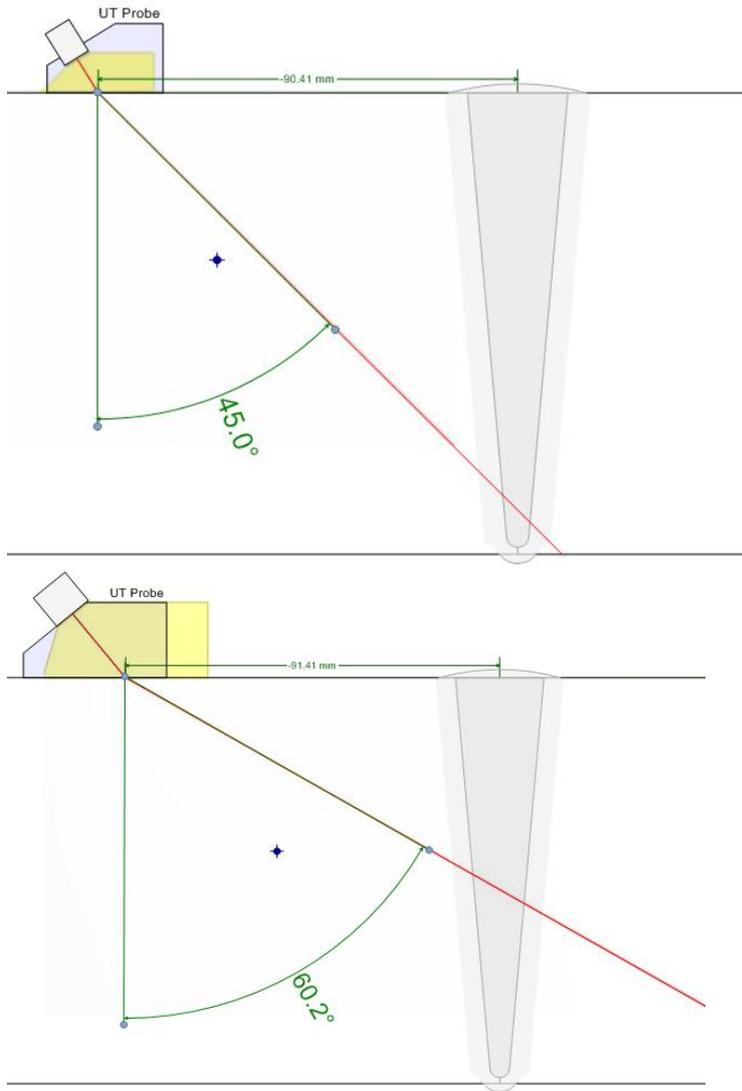   Steel Acoustic velocity shear mode 3230m/s
    Refracting Wedge velocity 2360m/s

Refracted Angle
45° and 60° beams were generated in Civa and the beams overlaid in BeamTool
The 45° probe was modelled with a 5MHz 6mm diameter circular element.
The 60° probe was modelled with a 5MHz 10x9.5mm rectangular element.

Figure 2　　　Matching centre rays in Civa and BeamTool for circular element 45° probe and rectangular element 60.25° probe in shear mode

The rays overlaid in Figure 2 are seen to be as near to identical as can be perceived on the images.
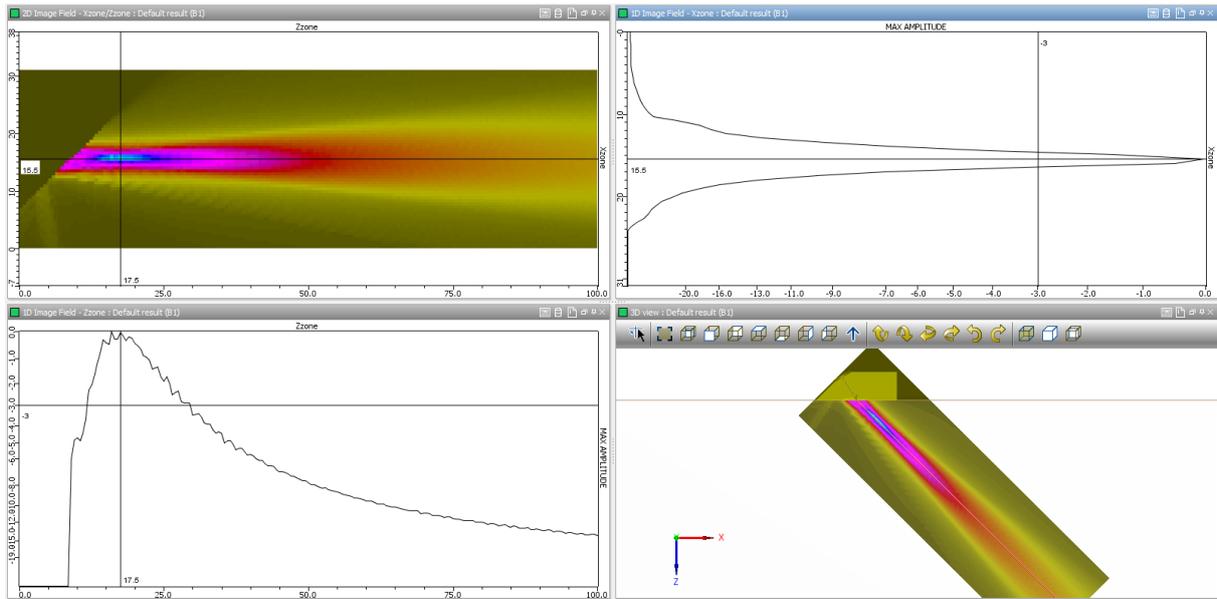
Beam Divergence

When using a pressure intensity plot such as provided with colour plots for beam illustrations, estimating beam divergence is not accomplished by simply placing a line at a particular colour change on the plot. This would result in concentric lobes as seen in Figure 3. The points connecting the equal pressure points trace out the so-called isobars. In images like Figure 3, the isobars are the lines at the colour-boundaries.
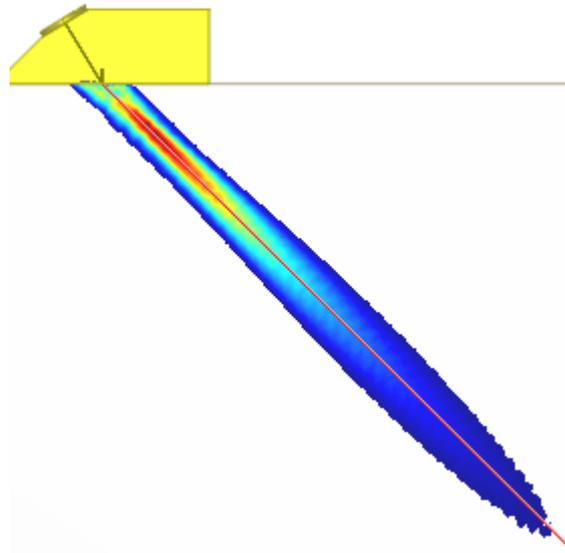
**Figure 3**   Lobes of equal pressure (isobars)

The physical determination of beam spread is usually done in pulse-echo by maximising the response from a small side drilled hole (SDH) and then moving the probe until the amplitude reduces to half the peaked amplitude. This is the -6dB level in pulse–echo. Determining beam spread from computer generated plots can be done similarly but using the -3dB drop points (as would be done for the through-transmission technique). Note that when the process is done with traditional manual techniques using the IOW block, the "slices" through the beam are made at a constant depth so that the distance from the exit point to the hole at the back of the beam has a shorter path and the distance to the hole for the front of beam has a longer path. The effect of these path differences is normally compensated by the operator constructing a distance amplitude correction curve and dropping the amplitudes to the DAC curve.

Figure 4 illustrates the colour plot of the beam pressure (upper left and lower right). Amplitude of the pressure along the axis is indicated as a curve in the lower left box. The cursor perpendicular to the beam axis is located at 17.5mm and coincides with the peak amplitude on the beam axis. This makes a slice of amplitude across the beam at the near zone (last maximum prior to continuous pressure decay). Note that because the Civa modelled plot is being assessed at a constant time along the beam axis for both the front and back of beam, there is no need to make DAC curve corrections as would be the case for manual measurements.

**Figure 4**   Beam pressure plots and echo-dynamic curves

By measuring the displacement from the beam axis to the points where the pressure drops by 3dB on these plots, a series of points is formed indicating the beam divergence. The lines connecting the 3dB drop points at each increase point along the beam axis provides an indication of beam divergence. (Note that the -3dB boundary in the one-way transmission is equivalent to the -6dB value for pulse-echo measurements). Figure 5 is a series of the beam cross-section echo-dynamic plots at 17.5mm, 30mm, 50mm, 70mm and 90mm from the probe.
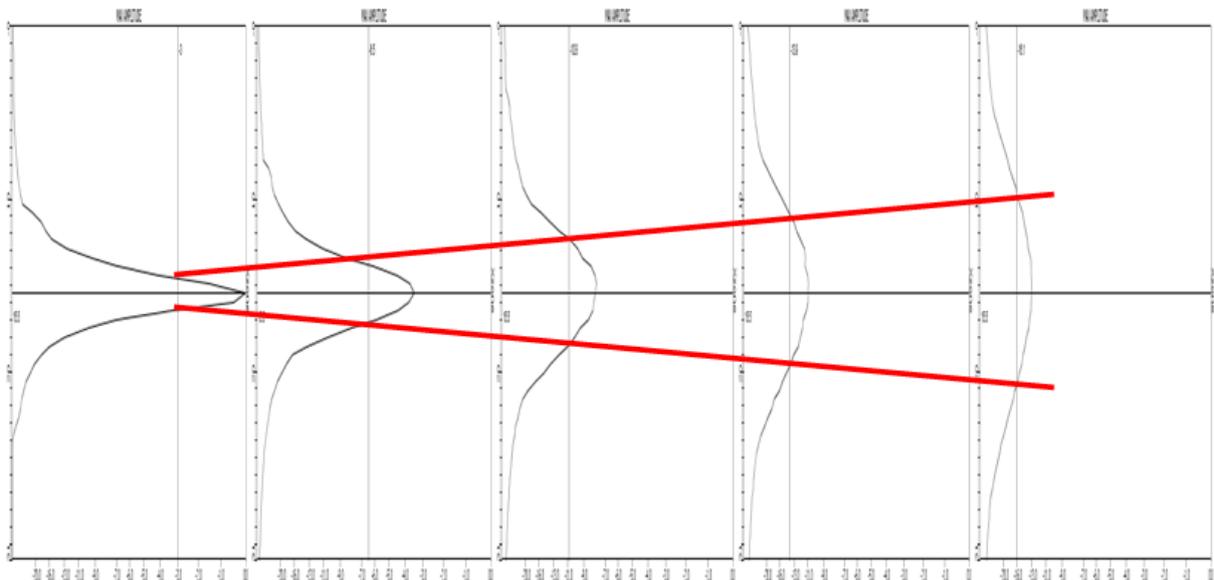
Figure 5   Amplitude plots at 5 beam cross sections and lines drawn at -3dB offsets.

Displayed as in Figure 5, the beam divergence is approximately symmetrical. However, upon a more precise measurement of each point along the axis and plotting the actual displacement to the -3dB drop points, we can plot a graph that illustrates a slightly non-symmetrical aspect of the beam divergence. Figure 6 indicates the values of the trend lines and the approximate

divergence when extrapolated to the origin. This indicates 3.4° as the half angle of divergence for the back and 3.7° for the front of beam.
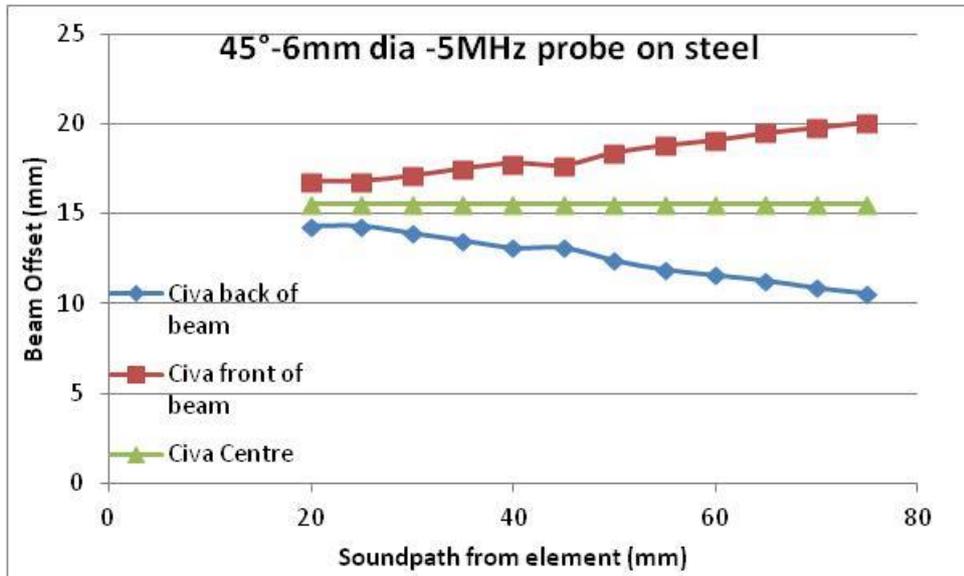
Figure 6   Beam divergence from Civa plots for 6mm diameter 5MHz 45° in steel

In Figure 7 we overlay the Civa pressure plot for the 45° beam for the 6mm diameter 5MHz probe on a steel block. Comparing the calculated beam spread from Civa to the illustrated beam from BeamTool we see a slight but noticeable difference.
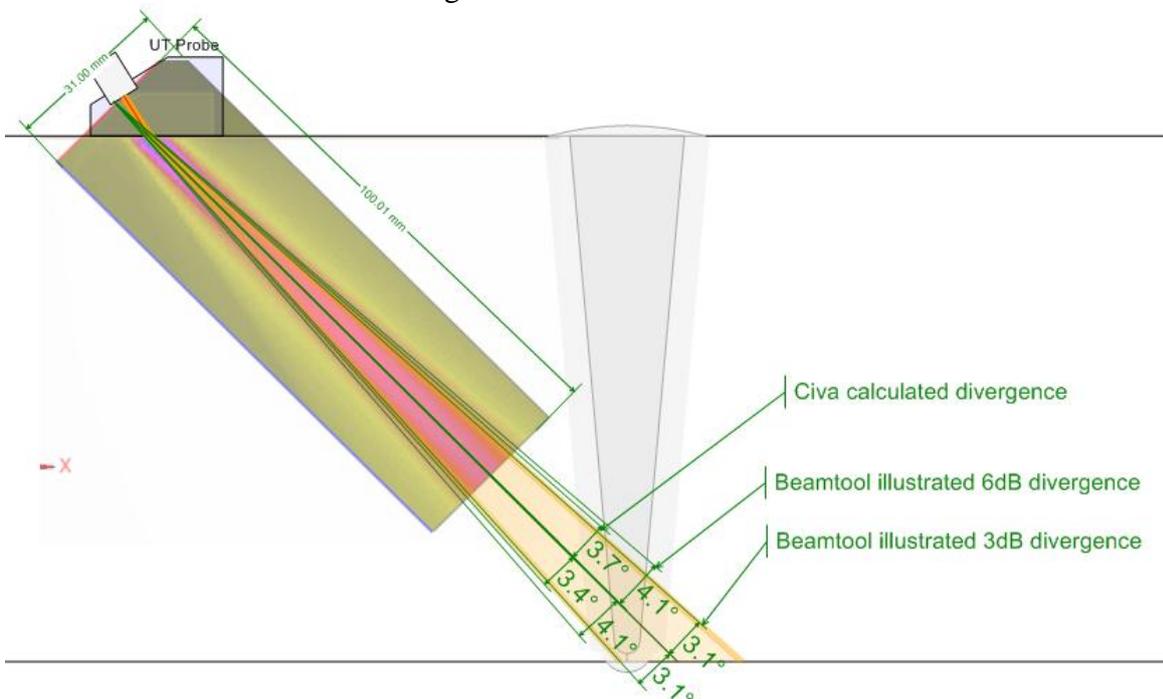

Figure 7   Comparing beam divergence for 5MHz 6mm diameter probe in steel

In the calculator box BeamTool indicates an option to illustrate different divergence constants. When the 3dB divergence is selected for the 5MHz 6mm diameter element the angle of beamspread (i.e. two times the divergence) is given as 6.3°. This is the value obtained when the constant k=0.51 and corresponds to the pulse-echo 6dB drop.

When compared to the 6dB spread calculated from the Civa values we see the BeamTool is within 0.3° and 0.6° and both under-estimate the divergence calculated by Civa. BeamTool indicates a symmetrical divergence whereas the Civa calculations indicate a slight asymmetry.

Since the equations for round and rectangular probes are slightly different, a model was made for a 2.25MHz probe with a square shape, 20x20mm. The model was plotted for a 150mm path from the element configured to obtain a nominal 60° refracted beam. (See Figure 8).
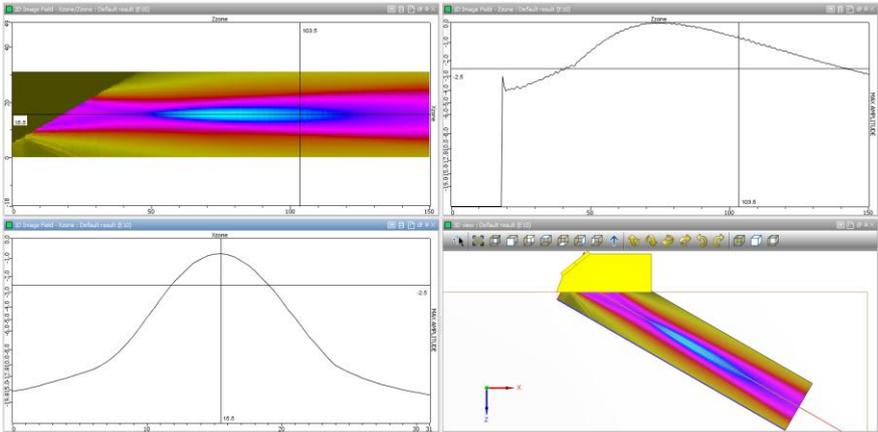

Figure 8   Civa-modelled 2.25MHz 20x20mm probe 60° refracted in steel

Plotting the -3dB drops from the Civa model the beam divergences were estimated to be 2.2° (lower half divergence) and 2.6° (upper half divergence). See Figure 9.
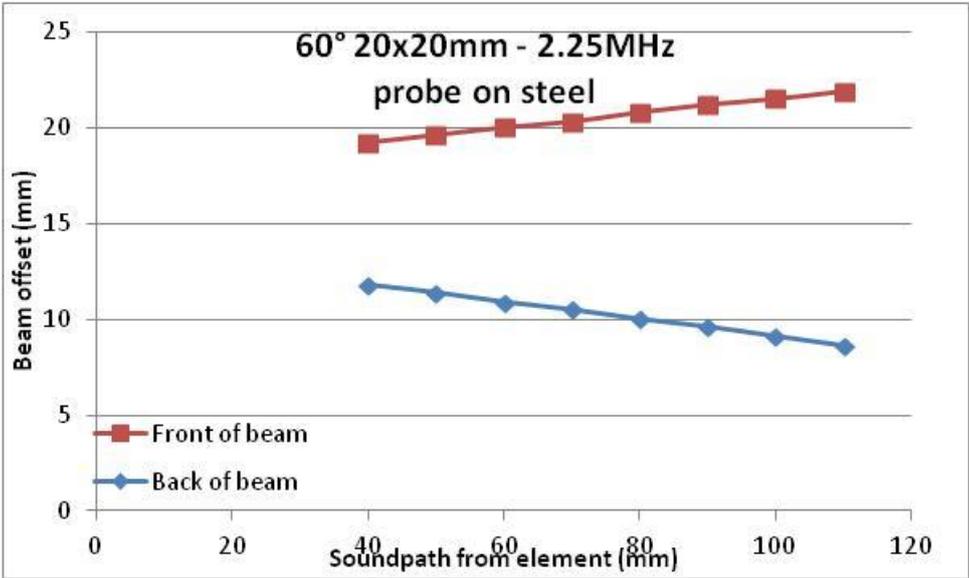

Figure 9   Beam divergence from Civa plots for 20x20mm 2.25MHz 60° in steel

BeamTool text display for the calculated beam spread for this probe indicates 3.7° which, if assumed symmetrical, provides a half-angle of divergence of 1.9°. This is very near the 2.2° and slightly less than 2.6° angles predicted by Civa. The Civa model is over-laid on the BeamTool image in Figure 10.
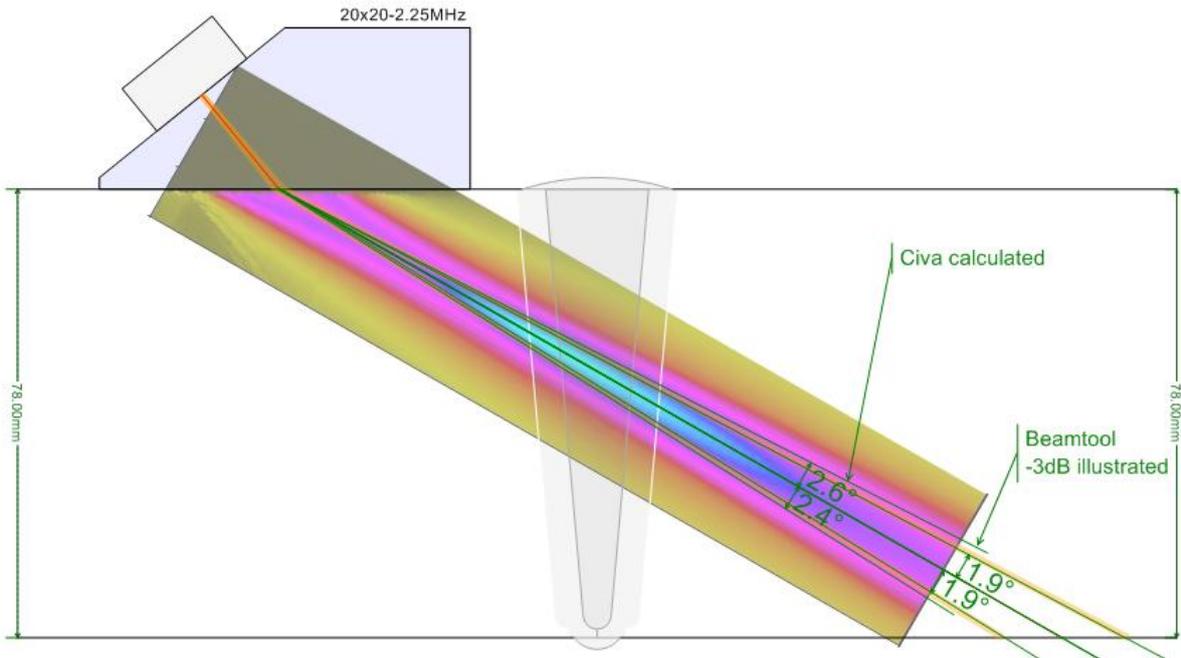
Figure 10   Comparing beam divergence for 2.25MHz 20x20mm probe in steel

Modelling a phased-array probe with 16 element 2.25MHz nominal frequency and a 19.5x20mm aperture (14 elements 1.5mm wide with 2mm pitch) a similar image is formed. The 19.5mm aperture increases slightly but does not noticeably affect the expected spread and BeamTool predicts the same divergence of about 1.9° for the -3dB drop in the one-way path (equivalent to the -6dB in pulse-echo).
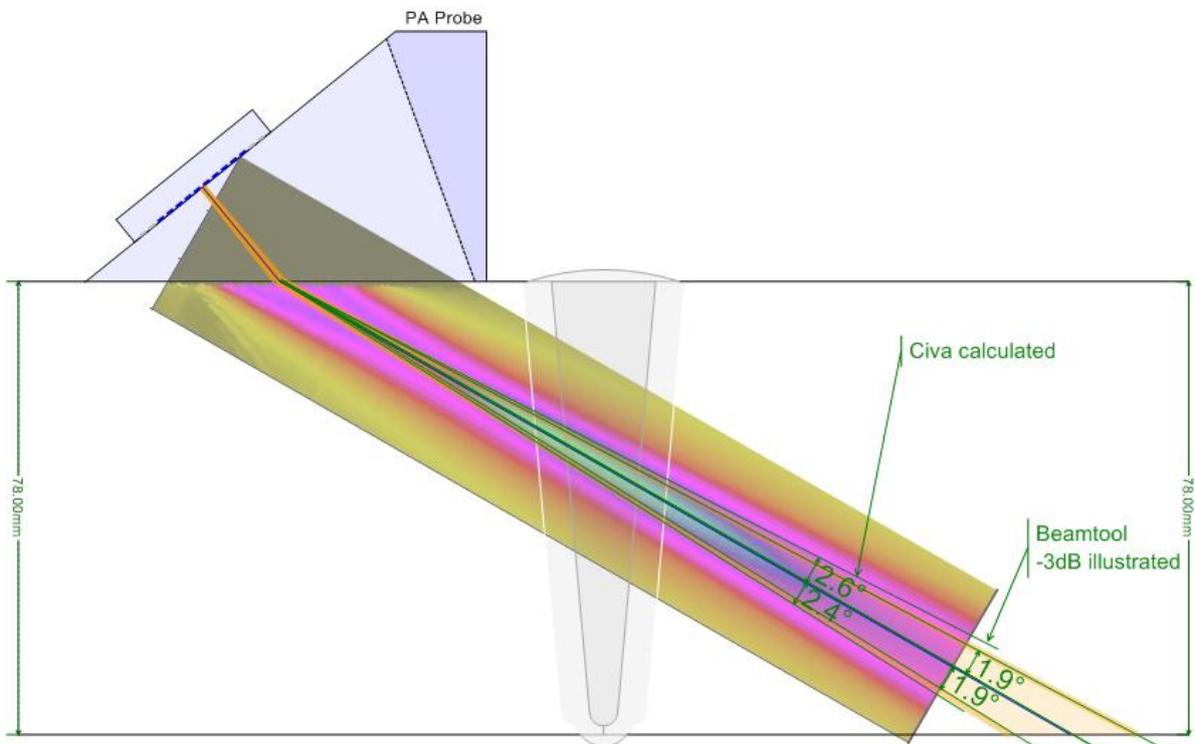

Figure 11   Comparing beam divergence for 2.25MHz PA probe with 19.5x20mm aperture

Near-field Distance

Civa does not locate a specific point as the near field when generating a beam pressure plot. This is determined from the echo-dynamic curve along the beam axis. BeamTool locates the end of the near field by a simple series of dots that end at the end of the calculated near field. Provision is made in the near field computation to accommodate the effects of the wedge path.

The near field distance is another parameter that is affected by wavelength and diffraction effects. For the large aperture 20x20 monoelement or 19.5x20 PA probe aperture, the Civa plot indicates the near-field distance to be 77mm from the probe at 60° refracted angle. BeamTool indicates it is approximately 88mm of soundpath from the probe (see Figure 12).
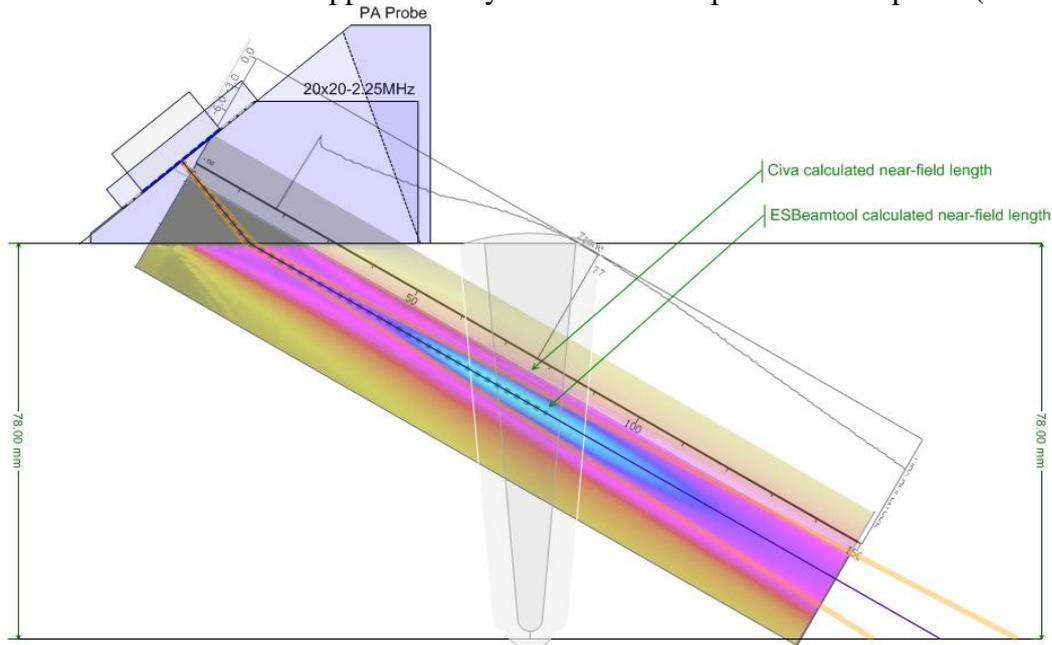
Figure 12   Comparing near-field length for 2.25MHz PA probe with 19.5x20mm aperture at 60° refracted angle

For the smaller higher frequency probe at 45° refracted angle, Civa indicates a 17mm soundpath from the element face to the end of the near-field while BeamTool estimates 16.2mm as indicated in Figure 13.
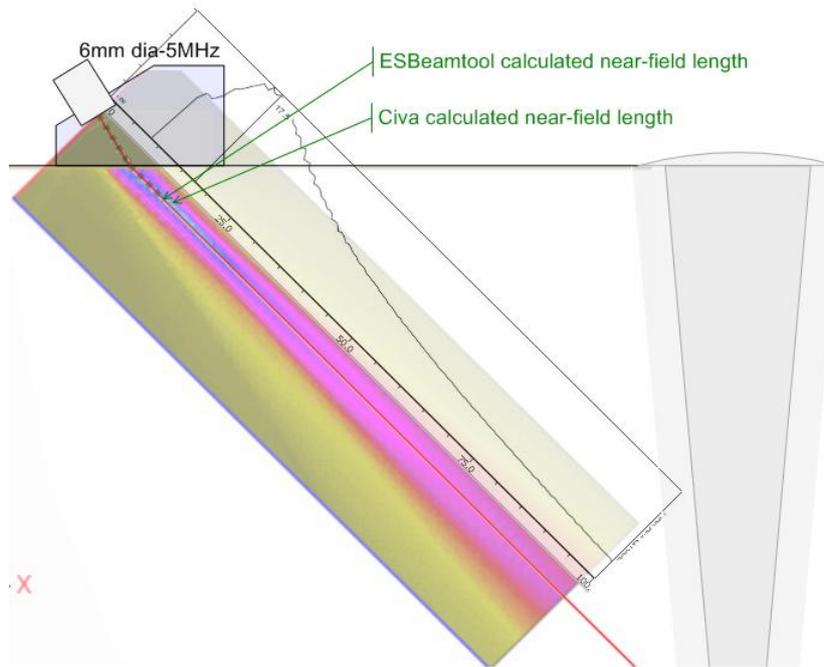
Figure 13   Comparing near-field length for 5MHz 6mm diameter probe

4. Conclusions

Comparing the images provided by BeamTool to those generated by Civa provides a means of validating the empirical values typically used in the NDT industry. Since the values of Snell's law are used in both software programmes, the angle of refraction for the central ray of the beam is identical in both programmes.

Beam spread from a normal incidence will provide a symmetrical divergence either side of the central ray. However, due to spherical divergence of the beam there is a tendency for the beam to make slightly different incident angles when the beam is incident at some oblique angle to an interface. This, in addition to the echo-transmittance variations with incident angle, add together to result in a slightly non-symmetrical divergence. This function of diffraction effects is not dealt with in raytracing representations of the beam. Civa modelling provides a reasonably accurate representation of the pressure distribution of a refracted angle beam because it addresses diffraction effects. BeamTool attempts to correct for these effects empirically. The BeamTool results in a symmetrical representation of the beam divergence that is a reasonably close approximation of the diffraction model (typically within 0.5°).

Near zone estimates are an important factor when considering focussing in a phased array application. Knowledge of the near zone will allow the operator to estimate an effective aperture if focussing is required to be applied. Over the limited range of frequencies, apertures and angles assessed in this paper, the empirical methods used by BeamTool provide distances within 1mm to 11mm of the diffraction calculations made by Civa. For other apertures the variations will be greater. This is the subject of a separate paper.

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