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CIVA Confirmation of Frequency Dependence of TOFD Lateral Wave

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Abstract
Pulse-duration (ring-time) of the TOFD (Time of Flight Diffraction) lateral wave has been assumed to be based on the nominal frequency of the probe. With the improved damping used for TOFD applications, these probes now have had their ring-time reduced to about 1.5 cycles. As a result of the short pulse duration, the bandwidth of these probes is greatly increased. However, assumptions based on the nominal frequency are only approximations. Underlying physics of beam divergence exacerbate these assumptions when considering the frequency content of the lateral wave. CIVA simulations are used to illustrate how using the nominal probe frequency underestimates the actual dead zone extent of the lateral wave.

Keywords: TOFD, lateral wave, CIVA, pulse duration

1. Introduction

In a recent paper [1], the geometric approximations used by Silk [2] and incorporated in standards [3, 4, 5] were shown to break down when the assumption that *the ultrasonic energy enters and leaves the specimen at fixed points under the probes,* cannot be held to a relatively small variation. Equations found in those standards can be reasonable approximations when the probe aperture is relatively small (e.g., 3-6mm diameter).

Although not codified, another assumption made in recent times has been to use 1.5 times the pulse-duration of the nominal frequency of the probe to calculate the dead zones associated with TOFD. This seems to have come from a statement by Charlesworth [6] that although the earliest iterations of TOFD equipment used narrow bandwidth probes, it was not until TOFD probes began to be made using heavily damped elements, such that the pulse was reduced to 1.5 cycles, did the resolution by TOFD get improved.

Using 1.5 times the nominal frequency as the pulse-duration of TOFD probes is perhaps convenient; however, it is not necessarily accurate. The primary source of probe damping is the metal-powder-loaded epoxy used as backing to the piezo-element. Other factors can also be a part of the damping, such as the applied voltage shape and subtle loading effects that can be had by front-loading with pressure variations from such things as how tightly the probe is secured to the refracting wedge or the pressure that the operator applies to the probe during scanning.

Perhaps the most significant deviation from the assumed wavelength being based on the nominal frequency is where in the beam profile the pulse is measured. It is well known that the

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rate a beam diverges is dependent on the probe frequency (or wavelength) and aperture. Divergence is inversely proportional to frequency and aperture as illustrated in Figure 1.

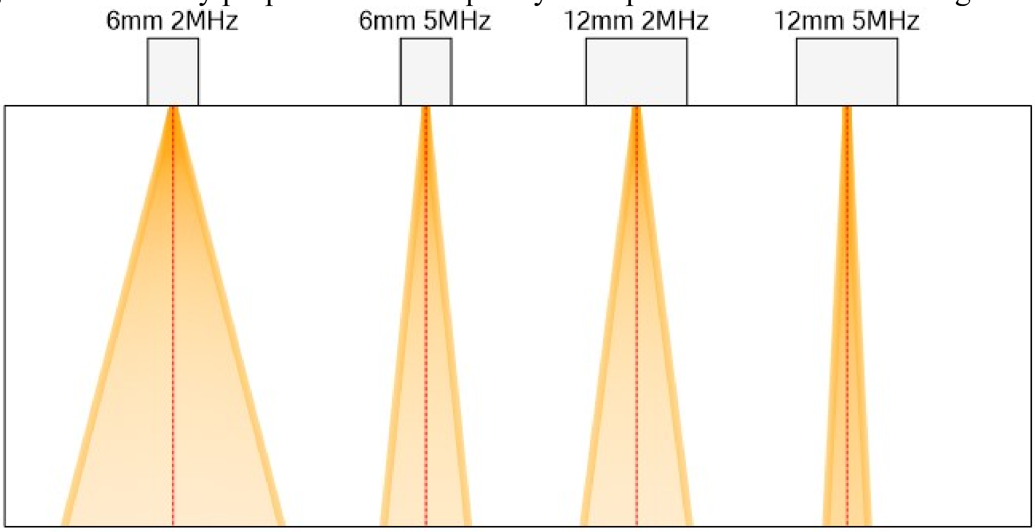


Figure 1 Beam spread variations with aperture and frequency

This representation is somewhat deceiving as it is based on continuous wave excitation at a single frequency or wavelength. Probes used in most industrial applications are operated in pulses rather than continuous excitation. When we look at the frequency content of the impulse shape of a probe it can be seen to contain more than one frequency. The shorter the pulse-duration the broader the frequency content. Figure 2 illustrates a 2.25MHz pulse with 9 cycles (left) and 1.5 cycles (right). The -6dB frequency content of the 9 cycle pulse ranges from 2.02MHz to 2.47MHz whilst the 1.5 cycle pulse ranges from 1.29MHz to 3.21MHz. This is the difference between a 20% bandwidth and 85% bandwidth.

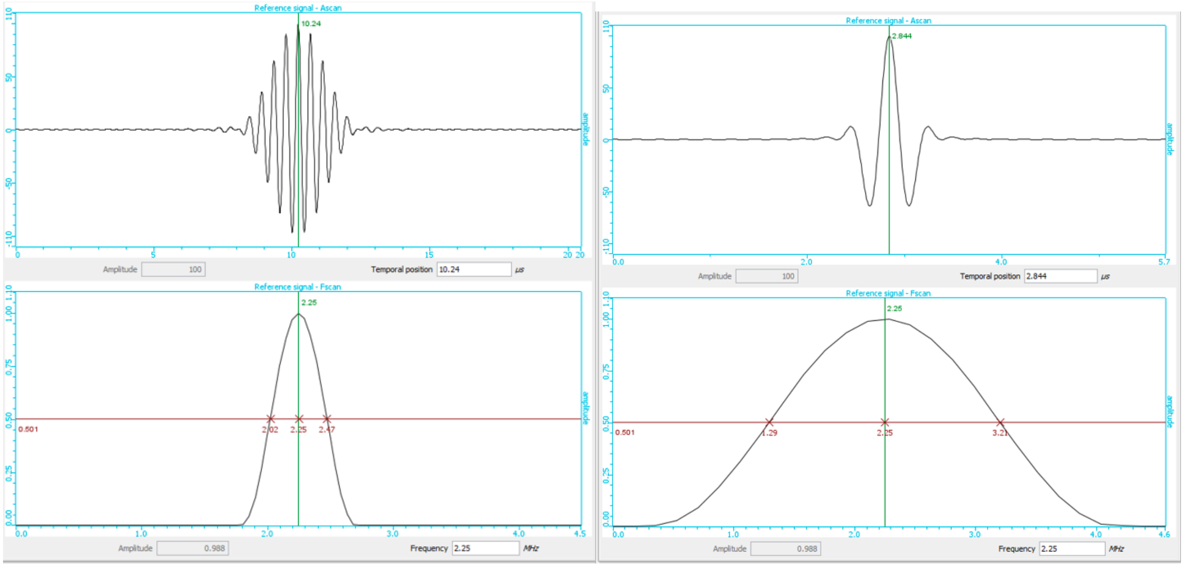
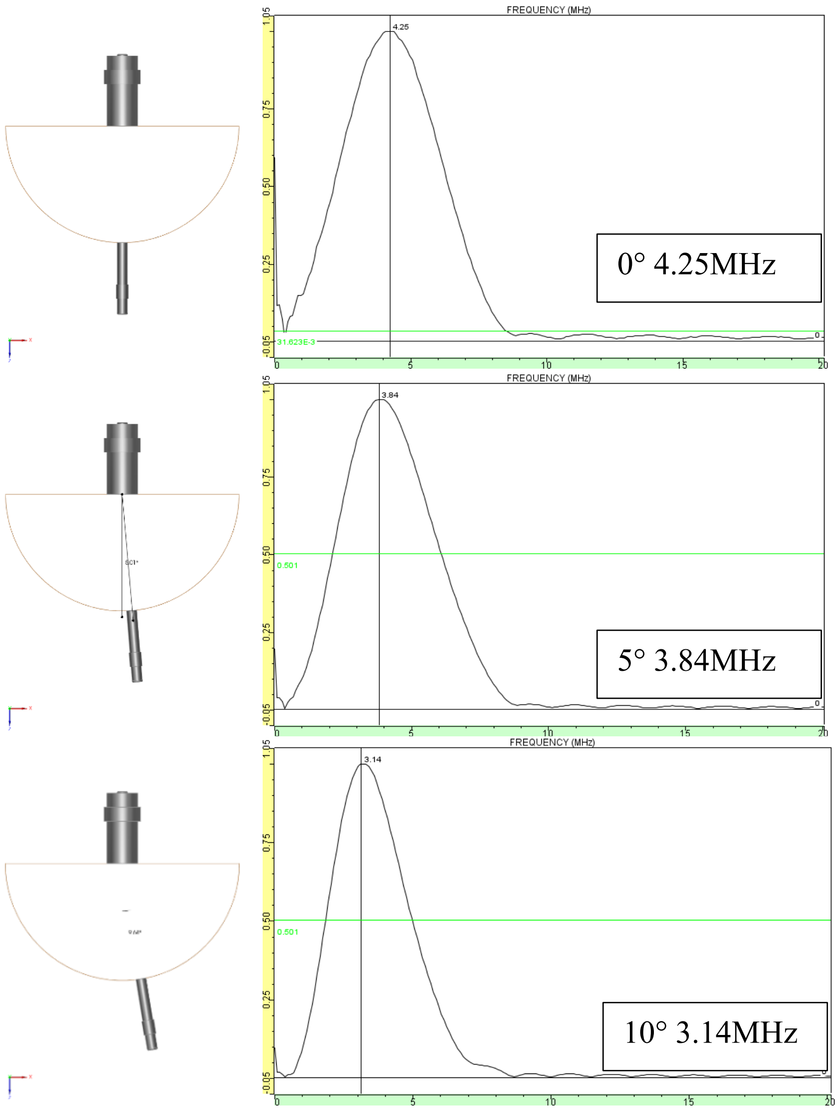


Figure 2 Effect of pulse-duration on frequency content

With a well-made TOFD probe, designed to ring with just 1.5 cycles, the pulse will therefore contain a wide range of frequencies. And since beam spread is a function of frequency, the lower frequency content will spread more than the higher frequency content.

2. Confirming Frequency Drop using CIVA

A simple through-transmission model was made using CIVA simulation software to illustrate the reduction of frequency as we move off axis of the centre of the beam. A nominal 5MHz 6mm diameter probe with 85% bandwidth was configured as a transmitter and a smaller 2mm diameter probe as a receiver. These were placed in contact on a semi-circular block of steel with a 50mm radius. The receiver probe was initially positioned directly opposite the transmitter and then moved in approximately 5° increments away from the beam axis. Probe positions and associated FFTs are seen in Figure 3.



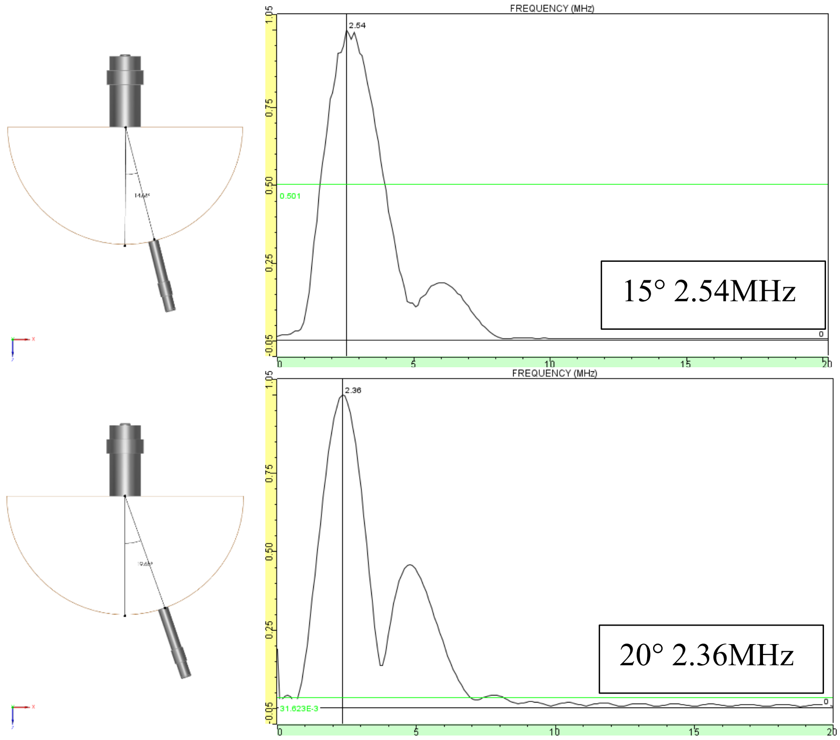


Figure 3 Frequency downshift with offset from centre of beam

It is worth noting that even though the transmitter transducer is configured to pulse with a nominal 5MHz pulse, the received pulse at 0° offset from the beam axis has a slight downshift in frequency from 5MHz to 4.25MHz.

3. CIVA Evaluation of TOFD Lateral Wave Frequency

Having confirmed that the nominal frequency of the probe is not maintained when assessing the pulse off-axis of the centre beam, several TOFD configurations were made in CIVA and the frequency of the lateral wave measured.

Figure 4 illustrates a 10MHz probe with 85% bandwidth on a 70° refracting wedge. Used on a 15mm thick steel plate the 55mm PCS provides a 66% crossing point. The downshift in frequency is significant as the lateral wave is seen to be at 4.65MHz.

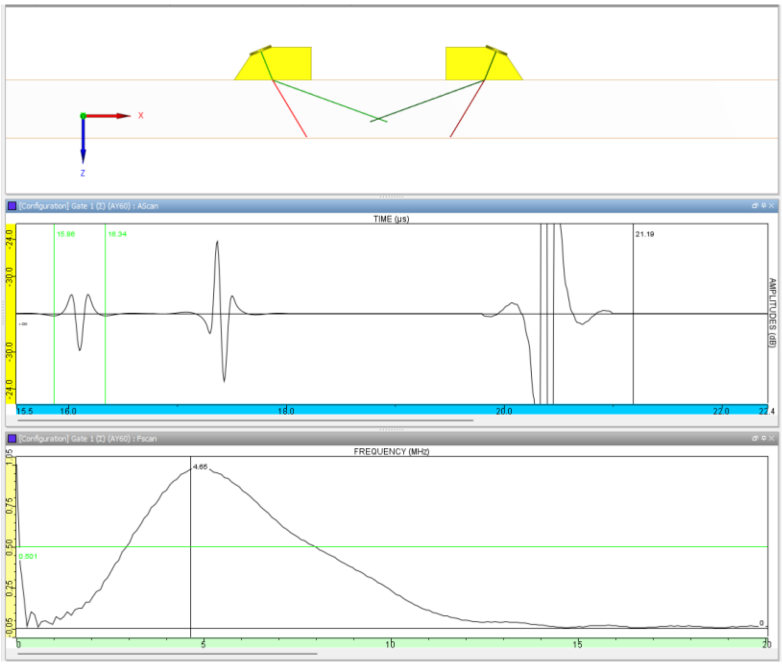


Figure 4 10MHz probe has a lateral wave downshift to 4.65MHz

Figure 5 shows the simulation of 5MHz probe with 85% bandwidth on a 60° refracting wedge. When placed on a 33mm thick steel plate, the 76mm PCS provides a 66% crossing point.

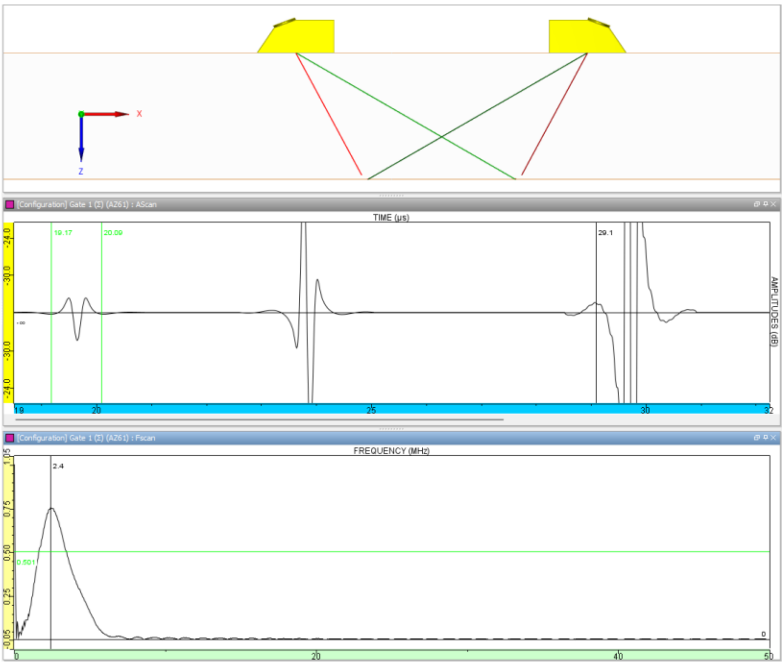


Figure 5 5MHz probe has a lateral wave downshift to 2.4MHz

Again, the downshift in frequency is significant as the lateral wave is seen to be at 2.4MHz.

4. Confirmation of Lateral Wave Frequency Downshift

To confirm that significant downshift also occurs on a real test piece, a pair of TOFD probes 6mm diameter 2.25MHz were placed on a 33mm carbon steel block 33mm thick using 60° refracting wedges. Using Beamtool [7], Figure 6 shows how this provides a nearly direct path to the receiver for the mode-converted compression mode off the shear mode that has reflected from the backwall.

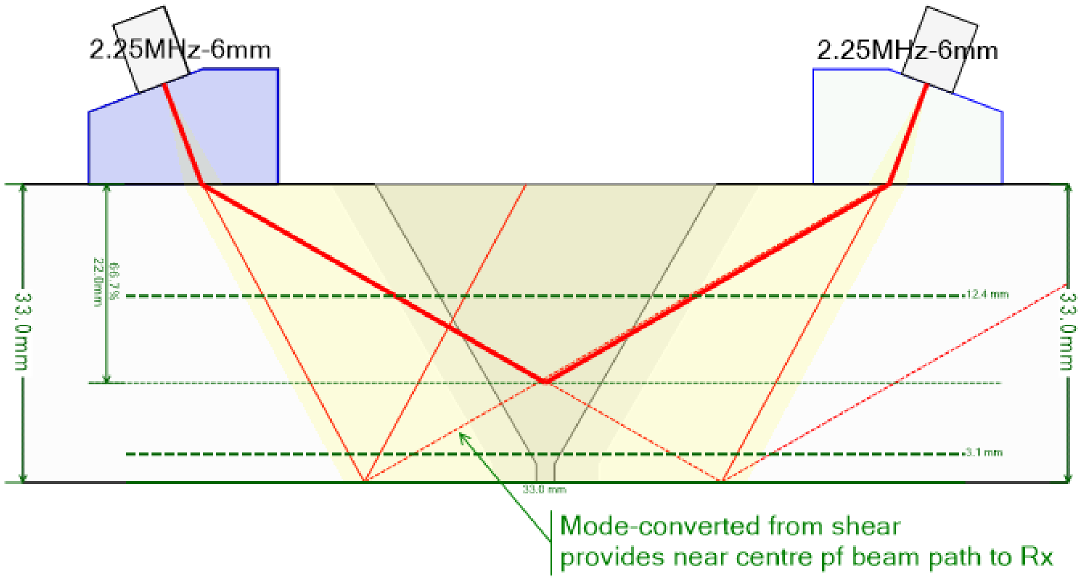


Figure 6 2.25MHz probe setup on steel plate

Having passed through slightly more than 20mm of polystyrene (Rexolite) the nominal 2.25MHz is already slightly downshifted, as polymers tend to preferentially allow lower frequencies to pass. When the signals are analysed in the frequency domain it is apparent that even at 2.25MHz there is a downshift in frequency content of the lateral wave relative to the nominal frequency. Figure 7 indicates the lateral wave having a centre frequency of 1.37MHz and when compared to the mode-converted signal which has less offset from the beam centreline, the downshift is very slight at 1.95MHz. (Note; amplitude of the mode-converted signal was decreased so as to avoid signal saturation).

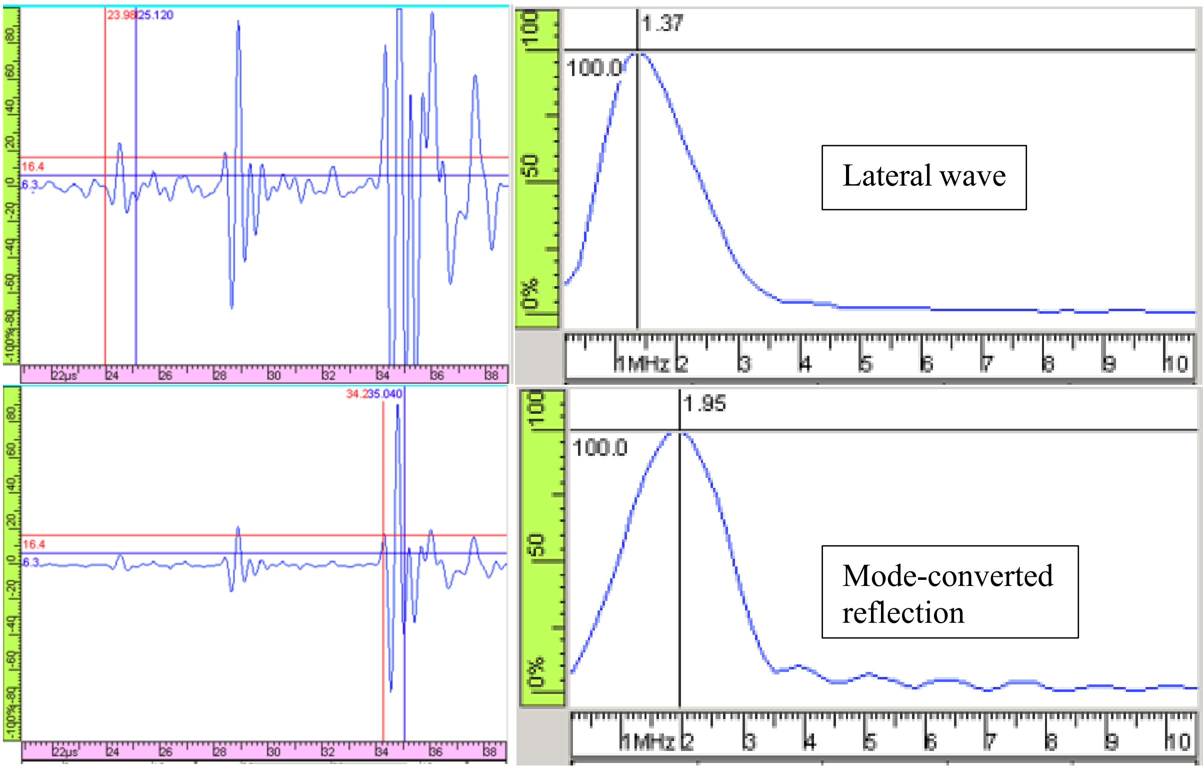


Figure 7 Frequency analysis of 2.25MHz probe in setup from Figure 6

To some extent, the effective lateral-wave dead zone is a qualitative judgement. The probe used may not be a perfect 85% bandwidth and surface conditions of the part inspected may deteriorate the signal quality. Figure 8 illustrates a scan of a single V weld 25mm thick scanned using a 6mm diameter 10MHz probe on a 60° wedge.

Assessing the lateral wave centre frequency, it is indicated as being 4.5MHz instead of 10MHz (similar to the downshift predicted in Figure 4).

At 10MHz and at 1.5cycles, the lateral wave dead zone is estimated to be 5.0mm. At 4.5MHz the equation estimates a dead zone of 7.6mm. With the lateral wave straightened and the zero-depth determined using the maximum positive peak, the qualitative estimate of the dead zone is approximately 7.1mm. Even then, the straightened lateral wave has some slight movement in time resulting in a non-uniform depth of dead zone.

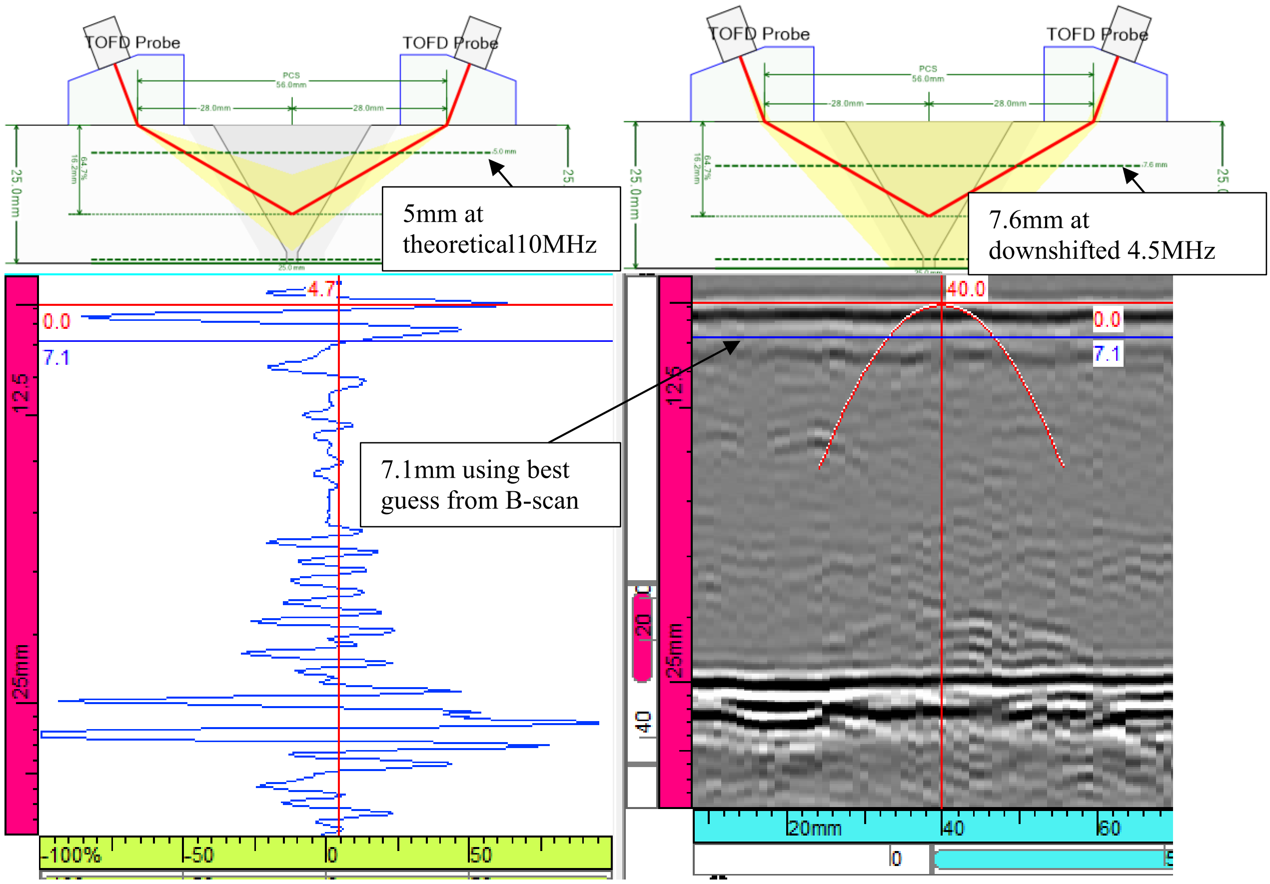


Figure 8 Dead zones for 10MHz 60° TOFD scan of weld in 25mm thick steel plate

5. Conclusions

Estimation of the lateral-wave dead zone, by using the pulse-duration of the nominal probe frequency, is simply a convenient approximation. Using the assumed 1.5 cycles of the nominal frequency to estimate the dead zone is likely to underestimate the actual dead zone.

Due to the natural downshift of frequency content by moving off the centre axis of a beam, the lateral wave will always have a longer duration than the value calculated from the nominal probe frequency.

Pulse duration is one of the variables found in three separate equations in the TOFD standards. In addition to the lateral wave calculation, it is a factor in flaw spatial resolution and backwall dead zone calculations. And since the flaw spatial resolution and backwall calculations are made at positions with less offset from the beam centreline, the downshift of frequency will be less than experienced at the lateral wave.

Acknowledgements

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