Flaw Resolution (Ed Ginzel, Nov. 2012)

Initially the NDT.net form discussion (http://www.ndt.net/forum/thread.php?admin=&msgID=45294&rootID=45194#45294) asked about the ability of a 7.5MHz phased-array technique to find a small 0.5mm tungsten inclusion.

This became a discussion on detection capability based on an old “rule of thumb” concerning wavelength and detect-ability. This rule of thumb may have developed from descriptions in the Krautkramer book (Ultrasonic Testing of Materials). Chapter 5 of that book related to Echo and Shadow of an Obstacle in the Sound Field. In discussing the fundamentals of the AVG (DGS) system, it is stated that the equations apply only to the very far field and for flaw diameters which are not much smaller than the wavelength. Krautkramer goes on to explain that “in the case of reflectors with diameters which are small compared to the wavelength, the processes concerning the reflection of an incidence sound wave usually are covered by the term “scatter”.

The transition from the concept of “reflection” to “scatter” is perhaps what the rule of thumb derives from; but it is not specifically stated as half a wavelength in Krautkramer. They state that as the flaw size decreases compared to the wavelength, the scattered wave becomes nearly spherical. Krautkramer also calls the scattered waves from the edge of planar flaws, “edge-waves”. We would be more likely to call these “tip-diffracted” waves in today’s terminology. Finally, they note that as a result of the reflected wave’s pressure being proportional to the third power of the diameter and inversely proportional to the square of the wavelength, small flaws soon defy detection because of the limited sensitivity of the instrument.

So we may reasonably assume that even very small flaws, with dimensions much less than the pulse wavelength, can be detected if there is sufficient gain in the instrument (and the surrounding matrix does not produces interfering scatter noise).

Detecting a small flaw will simply mean having adequate electronic gain to produce a response on the timebase that rises out of the electrical noise. To know with certainty that it is a flaw and not a grain boundary may be a different matter. The amplitude response generated by a probe from a received impulse will be a function of the returned pressure from a target. When multiple flaws are within the beam envelope, the retuned pressure will also depend on the proximity of the flaws to each other and the shape of the pulse-pressure from the probe at the depth of interaction. The ability of the system to resolve the indications from closely spaced flaws is termed resolution. A common issue with resolution is the lateral wave in TOFD. This is temporal resolution. Due to the pulse ring time duration, flaws occurring in the ring time may not be discerned outside of the ring time.

A separate resolution occurs for flaws at the same time but at different spatial positions (spatial resolution).

We illustrate spatial resolution using a simple Civa model setup.

Three probes were modelled. Each is a contact normal beam 10mm diameter and having a pulse bandwidth of 80%. Frequencies of 2MHz, 4MHz and 10MHz were used.
The beam profiles for these three probes radiating into steel are illustrated in Figure 1.

![Beam profiles for 10MHz, 4MHz and 2MHz 10mm diameter probes](image)

Figure 1  
Beam profiles for 10MHz, 4MHz and 2MHz 10mm diameter probes

Focal depths for the 3 probes and their spot sizes are tabulated in Table 1.

Table 1  
Beam Profile Data

<table>
<thead>
<tr>
<th>Probe</th>
<th>Frequency (MHz)</th>
<th>Near Field Depth (mm)</th>
<th>Spot Size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>9</td>
<td>3.9x3.8</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>16</td>
<td>3x3.2</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
<td>45</td>
<td>2.9x3</td>
</tr>
</tbody>
</table>

A steel block was modelled with 3 depths of flaws. Each set of flaws consisted of 10 small rectangular targets 0.1x0.1mm plus a 3mm SDH. The 3mm SDH was used to illustrate the sort of response that a UT technician might calibrate on in a typical weld inspection. The three depths used to illustrate resolution are 10mm, 20mm and 30mm from the test surface.

The small rectangular targets were arranged with increasing separation. The first 2 targets were separate by 1mm. The second and third were separated by 2mm, the third and fourth by 3mm, and so on with the 9th and 10th rectangular targets separated by 9mm. The 3mm diameter SDH was moved away from the small targets such that there was a 25mm separation between the last rectangular target and the centre of the SDH.

Each of the three modelled probes was then scanned over the targets along the line connecting the centres of each group. The scan path over the flaws is illustrated in Figure 2 as well as the cross sectional illustration of the flaws. Arrows are used to indicate the horizontal positions of the rectangular targets.
Composite B-scans are provided to illustrate the detections. The “composite B-scan” is merely the combined B-scan from each of the 3 probe movements so all three depths are illustrated simultaneously.

At a sensitivity that places the maximum response from the SDH at 100%, we see that only the SDHs are visible in all cases. (See Figure 3)
In each scan we see the ringing getting shorter on the SDH and the maximum amplitude occurs at a deeper point. Amplitude increases ranges from brown-green to pale blue. Maximum amplitude on the SDH will of course be nearest the near field for the probe used.

In order to detect the individual rectangle at the same amplitude as the 3mm SDH, gain is required. In the case of the 2MHz probe we add 55dB and then the rectangle just to the left of the SDH at 10mm depth is seen to achieve the pale blue colour. But of course, the SDH saturates (the edges of the responses from the SDH are truncated due to the limitation set on the gated computation window).

Note that the deeper targets are also detected. In the 10mm deep set of rectangular targets, we can see the last 6 targets separated one from the other. A-scan samples were made at 1mm increments and the targets with 6mm and more separating them have the amplitude drop to more than 6dB between them. A signal drop of 6dB or more would typically be used to determine if one target was resolved as separate from the other. In the row of targets at 20mm and 30mm depths, there are no spacings that provide a 6dB drop between adjacent targets (not even the maximum 9mm distance).
A similar processing of the responses is made for the 4MHz scan. In order to detect the individual rectangle at the far right at the same amplitude as the 3mm SDH 52 gain is required. This again saturates the SDH response.

In this case, the peak response from the rectangle comes from the second row (20mm depth). This of course closes to the near field distance of the 4MHz probe. Again, it is the last 6 targets separated one from the other at the depth closest to the near zone. The closest targets with a 6dB drop separating them are 5mm apart at 20mm depth. In the row of targets at 10mm depth only the last two targets separate by 6dB or more and at the 30mm depth the 9mm, 8mm and 7mm spacing can be considered resolved.

![Spatial Resolution Scan for 4MHz probe](image)

For the 10MHz scan in order to detect the individual rectangle at the far right at the same amplitude as the 3mm SDH, 49 gain is required. This again saturates the SDH response.

For the 10MHz setup the peak response from the rectangle comes from the third row (30mm depth). This depth is still 15mm from the 10MHz probe’s near field so we are detecting the targets in the near field. In Figure 6 it is only the last 5 targets at 30mm depth that are separated one from the other with more than 6dB drop between them. The closest targets with a 6dB drop separating them are 6mm apart at 30mm depth. In the row of targets at 10mm depth and 20mm depths, we can see the double peak effect as the edges of the beam pass over the targets.
In all cases illustrated in the Composite B-scans, the cluster of targets where small spacings occur provide larger responses than the individual targets we used to set the increased gain. This is a result of the total reflecting area of the multiple flaws under the beam causing greater amplitude.

In the beam profile plots we see that the spot sizes at the focal point are all approximately 3-4mm, regardless of the frequency. It is this dimension that will ultimately limit the spatial resolution that can be achieved.

Civa simulation software does not include a SAFT algorithm for post-processing but this could be used to improve the separation of closely spaced indications.

I placed an old 10mm diameter 5MHz probe on my USM3S and maximised response from a 3mm diameter SDH at 20mm depth. It required 46dB gain setting on the old instrument. I had 54dB gain in hand. Adding 50dB resulted in electrical noise up to 40% screen height. Perhaps a 0.1x0.1 mm flaw could be “detected”, but the signal to noise ratio would probably be problematic.