A Multi-Modality 3D Image Quality Assessment Standard

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Abstract
A prototype calibration standard has been developed to allow 3D imaging quality evaluation and sensitivity assessment for multiple examination modes. Well defined targets with characteristics only slightly different from the surrounding matrix are used to provide a subtle contrast in scattering that can be used to indicate the detection and resolution capabilities and of the examination method. With the ability to visually measure and locate the targets, the standard can also be used to gauge the accuracy of the 3D imaging display.
A demonstration of the concept has been carried out using a prototype model evaluated by micro-CT X-ray and high frequency phased-array ultrasound.

Keywords: microCT, X-ray, phased array, 3D imaging, ultrasonic, FMC

1. Introduction

Materials are often examined to evaluate the integrity of construction; or in medical applications, to diagnose for abnormalities. The preferred methods are usually non-invasive or non-destructive. Typical methods used include visual examinations (e.g. an eye-examination by an ophthalmologist), X-rays, ultrasound (used in both medical and industrial applications), and MRI (magnetic resonance imaging).
Each method has its limitations;

- Visual examinations require the object being viewed be transparent
- X-rays require volume density differences along the beam path
- Ultrasound requires acoustic impedance changes along the beam path
- MRI requires the presence of hydrogen (and the absence of ferromagnetics)

Because each examination method has advantages and limitations, it is often useful to apply multiple modalities when evaluating a specimen. This increases the probability of detecting unwanted conditions.

Goals of any non-destructive examination are varied. It may be as simple as verifying dimensions or it could be to establish physical properties. In some cases placement or dimensions of internal features not visible from the exterior can be established.

In medical and some industrial applications, calibration standards or “phantoms” are made having physical characteristics with known density and size properties for the purpose of verification of accuracy of an examination modality. The purpose would then be to check accuracy of imaging data.

A prototype phantom has been designed with the goal of allowing multiple methods of examination visualisation to be evaluated and readily compared to each other.

2. Phantom Design

Verification of the dimensions and placement of any targets in a solid becomes problematic when the material is opaque. Image quality indicators for X-ray are typically wires placed on the surface of an object. When assessing industrial ultrasound imaging, drilled holes of a known size can be used to establish imaging resolution. Some medical ultrasound targets have consisted of polymeric or steel rods in water or gels. Wires, rods and drilled holes have limitations in that they are generally useful for only a single modality of examination.

A prototype phantom has been constructed of a matrix of thermo-set elastomer with inserts of spheres composed of scattering agent embedded in a similar thermo-set elastomer. The scattering agent used has particle sizes on the order of 50 to 100 nanometres. Materials were chosen from a large selection of products previously described [1]. Approximate material properties of the main components are summarised in Table 1.

Table 1 Approximate Material Properties

Property	Clear Aqualene™	Black Aqualene™
Density (g/cc)	0.94	0.92
Hardness (Shore A)	50	52
Acoustic Velocity at 5MHz (m/s)	1565	1570
Acoustic Impedance (MRayls)	1.424	1.441

Figure 1 illustrates a prepared phantom with five embedded spheres. The block is nominally 75x75 mm square and 20mm thick. Spheres are aligned along the mid depth and are 2mm, 4mm, 6mm, 8mm and 10mm diameter.

Variations can be made to adjust hardness and acoustic velocity of both the matrix and targets. By maintaining the matrix clear the sphere locations and sizes are confirmed visually. Variations can also be made on the scattering concentrations and on the material, position, shape and size of the targets.

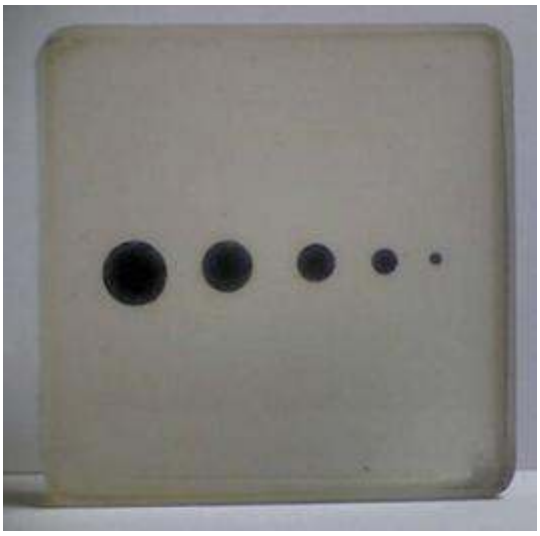

Figure 1 Prototype phantom

To confirm the sphere dimensions a microscope can be used for imaging. Although the moulds in which the targets were formed were accurately machined, some deviations occur due to shrinkage which will vary from one polymer to another. Figure 2 illustrates the nominal 4mm diameter sphere imaged through the matrix.

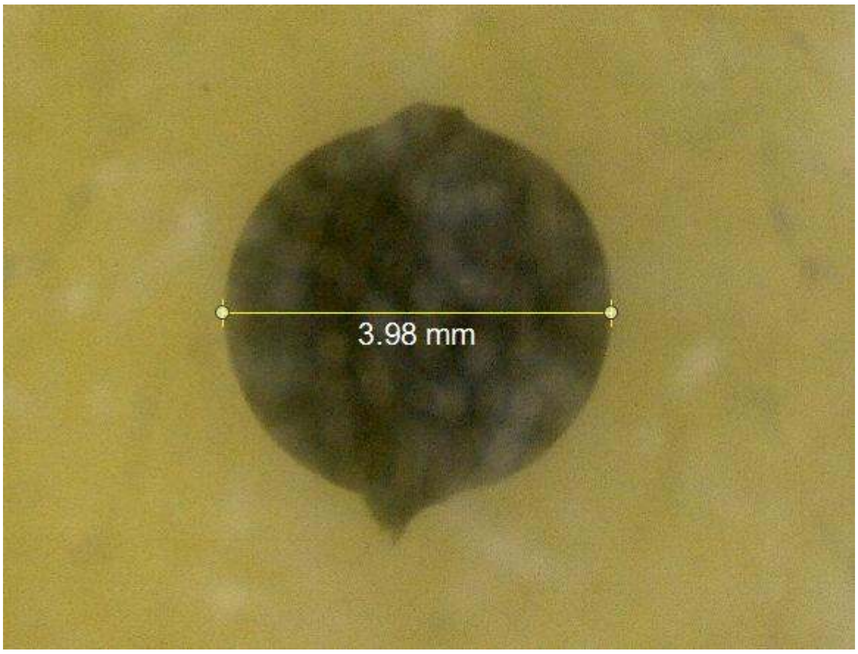

Figure 2 4mm diameter spheres photographed through matrix using microscope

Small tabs can be seen in Figure 2 where the sphere was detached from the connecting runner material in the mould.

3. 3D Imaging Modalities

To illustrate the use of the phantom as a multi-modal standard, micro-CT X-ray and high frequency ultrasound was used to image the spheres.

Micro-CT X-ray

Micro-CT X-ray was carried out on the phantom using 80kv and 50mA tube settings using a GEHC eXplore Locus Ultra Volume Micro-CT

When viewed from the left surface at the slice passing through all five spheres, the smallest sphere is clearly discerned as indicated in Figure 3.

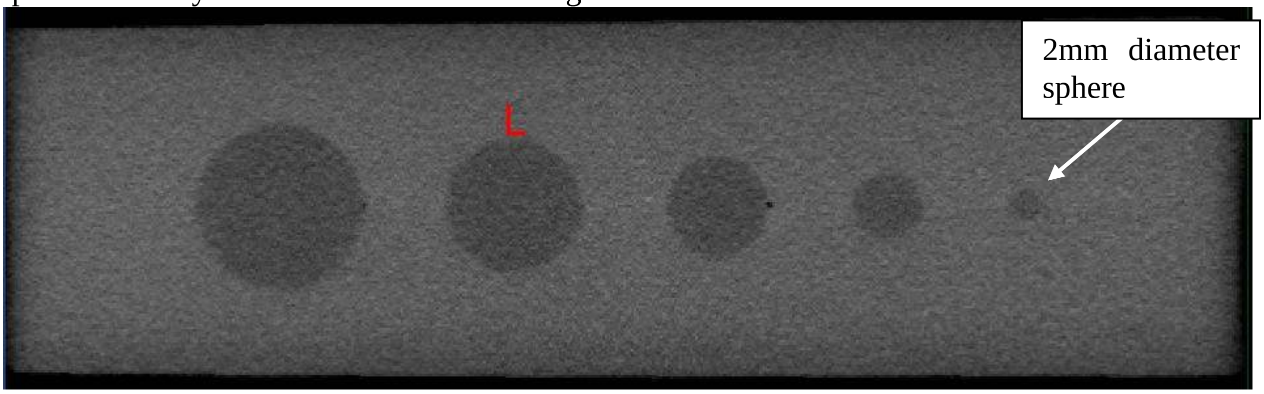

Figure 3 CT image of phantom along the axis of sphere alignment

In Figure 3 there is a faint black dot on the right edge of the third sphere from the left (i.e. the 6mm diameter sphere). This is evidence of a condition that exists around some of the spheres.

In Figure 4 another slice is extracted just 2.4mm into the plane of the paper from that in Figure 3. Here it is possible to see voids forming at the midpoints of the 10mm and 8mm diameter spheres. The largest of these voids is 0.8mm across.

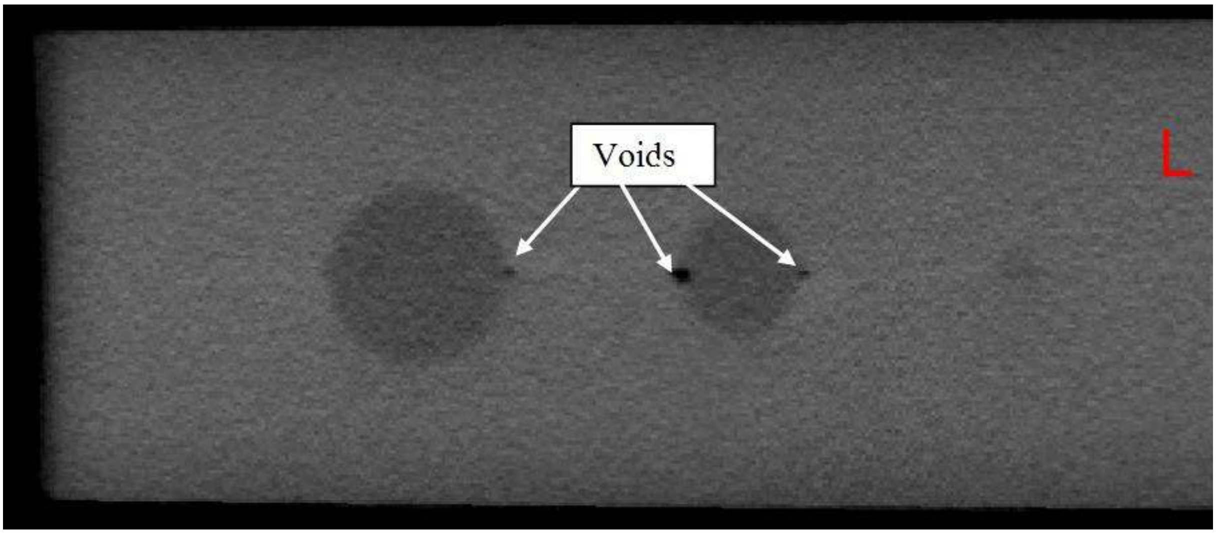

Figure 4 CT image of voids at the mid depth points adjacent to 10mm and 8mm diameter spheres

High frequency pulse-echo phased-array

Pulse-echo high frequency phased-array ultrasonic imaging was used on the phantom using a 20MHz linear array. The array was driven by a Vevo 2100 made by VisualSonics. The probe was a VisualSonics MS-250 linear array with a nominal centre frequency of 20 MHz, element pitch is about 0.115 mm and has 256 elements. The passive aperture (element elevation) is about 3.3 mm.

Delay laws used consisted of an active aperture of 64 elements, transmit focusing at the midpoint of the 20mm thickness of the phantom. In the receive mode, a dynamic depth focusing was used over the full thickness range.

The scanning apparatus used had a limited travel of only 45mm. As a result, the full 75mm length of the phantom could not be covered in a single pass. Figure 5 illustrates the four smallest spheres encompassed in a single scan.

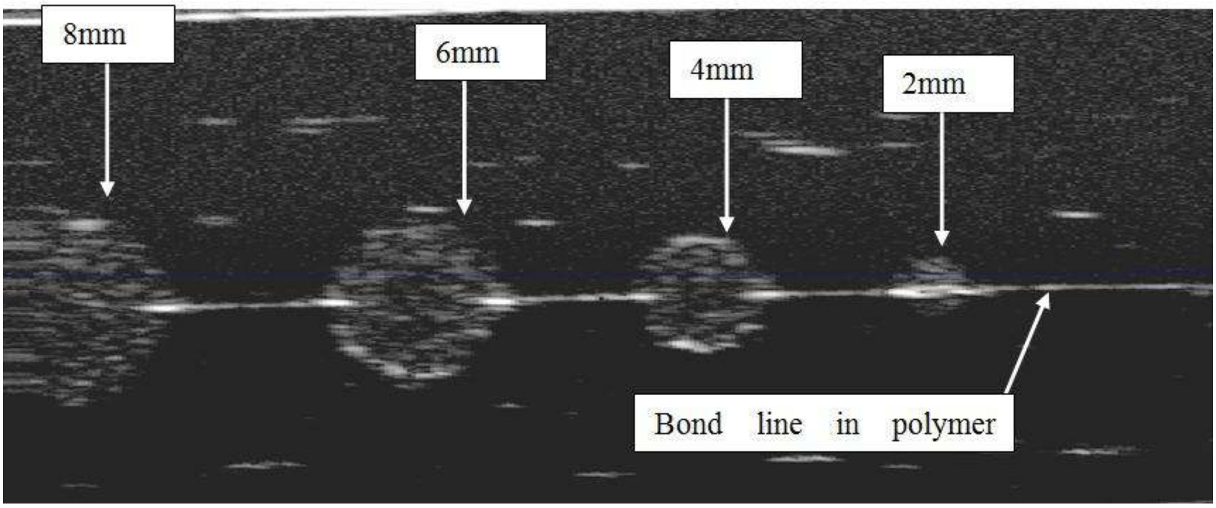

Figure 5 Phased-array ultrasound image of spheres

Whereas the CT X-ray images disclosed that small voids existed next to the spheres, the phased-array ultrasound clearly indicates a signal that aligns with the midpoints of all of the spheres and this can be attributable to partial bonding not evidenced by the CT X-ray scan. The small horizontal white lines in the matrix outside the sphere volumes are attributable to small micro voids in the matrix.

When viewed from the top surface perpendicular to the bond-line, the shape and extent of the poor bond condition is more apparent. The intermittent bond zone is indicated in the top-view seen in Figure 6.

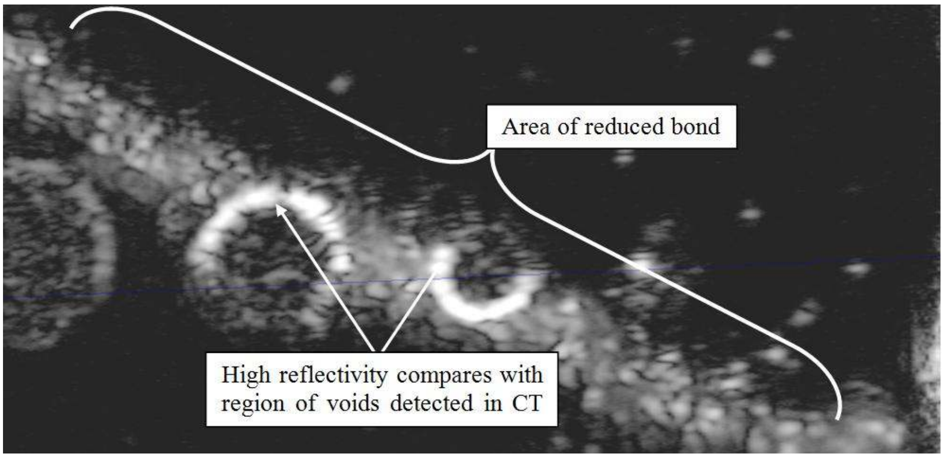

Figure 6 Phased-array ultrasound top view imaging region of reduced bond passing between 6mm and 4mm diameter spheres

Full Matrix Capture Imaging

In recent years the industrial sector has developed a phased array technique called Full Matrix Capture (FMC) [2, 3, 4]. This is used in conjunction with a post processing of data called Total Focussing Method (TFM). After data processing, 3D imaging is also possible with the TFM displays.

The 3D Image Quality standard was scanned using an industrial system assembled by Eclipse Scientific. The phased-array system used an OEM-PA system with a 64 element 10MHz linear array probe (0.5mm pitch, 10mm passive aperture).

Figure 7 illustrates the probe placement with the active aperture covering the 3 largest spheres. Figure 8 indicates the raw TFM image overlaid with a scaled model of the probe.

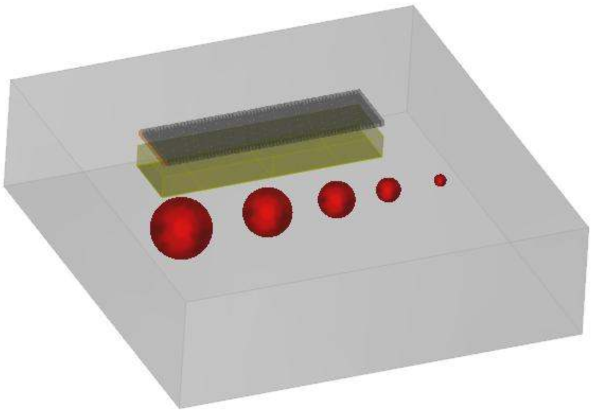

Figure 7 FMC probe placement relative to spheres

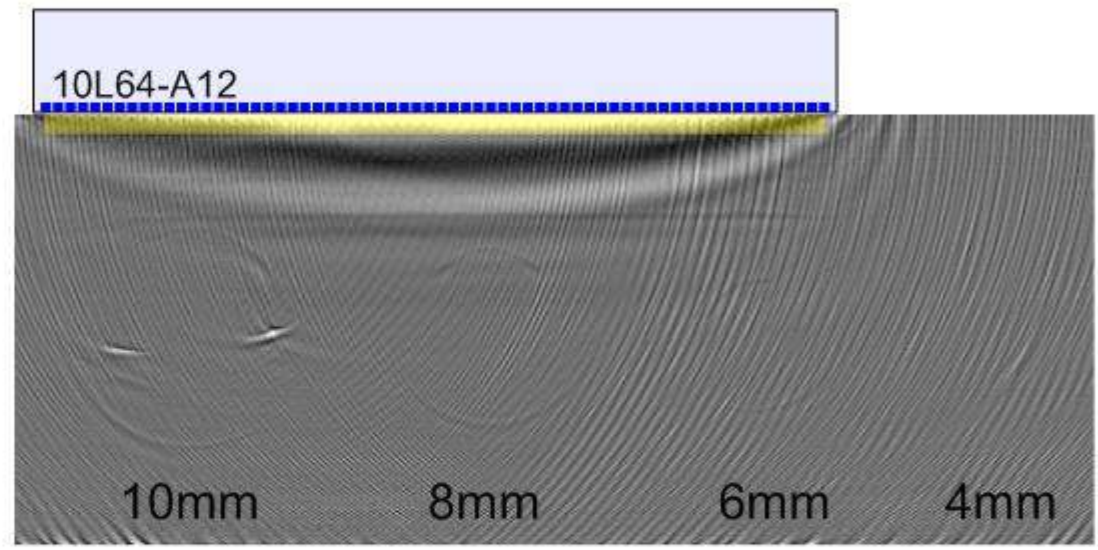

Figure 8 TFM reconstruction raw image indicating location of 4 spheres

Figure 8 indicates how the TFM reconstruction of the cross section can also provide a good indication of the circular dimensions of the targets. Since the FMC process fires only a single element at a time, the pressure introduced into the volume is low compared to focused pulse echo.

In Figure 9, image smoothing has been applied with slight increase in contrast to improve the visibility of the imaged shapes. By ensuring that the dimensions are correctly compensated, confirmation is had that the imaging software is correctly configured. The black circles were drawn at exactly 10mm, 8mm and 6mm diameters and overlaid on the TFM image in Figure 9.

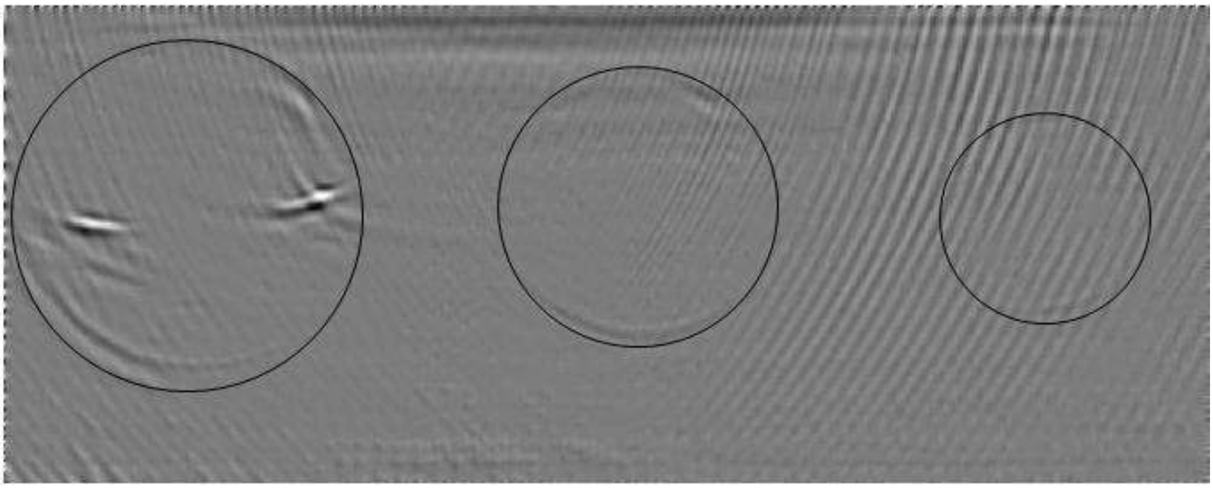

Figure 9 Comparing TFM reconstruction of 3 spheres with scaled circles

Because the nature of X-rays is such that they are not time dependent, it is expected that the imaging dimensions they produce are independent of the materials used. However, ultrasonic imaging is time-dependent. If the matrix and spherical targets are not correctly matched for acoustic velocity, the circular shape is not preserved in the imaging.

Civa modelling shows how the arrival time of material with slightly higher velocity would result in the far surface of the sphere plotting nearer and thereby distorting the imaged shape. Figure 10 uses Civa TFM reconstruction of a sphere on the left with closely matched acoustic velocities (1570m/s matrix and 1560m/s sphere) compared to a matrix with 1570m/s and on the right side a sphere made from an epoxy with acoustic velocity of 2490m/s. Using the 2mm diameter sphere as an overlay, the plotted ultrasonic response from the far surface of the sphere would appear to occur much earlier than it actually is relative to the upper surface.

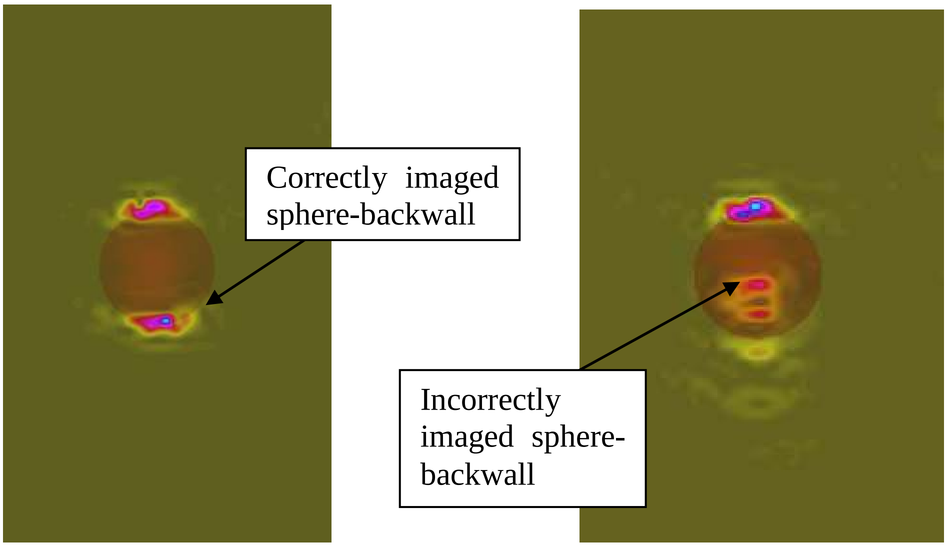

Figure 10 Volume plotting distortion when acoustic velocity of spheres is not matched to matrix (matched velocity left, unmatched velocity right)

As a result of the matrix and targets having closely matched acoustic impedances, the far side of the sphere is detected in both the pulse-echo and FMC techniques. Had the sphere contained excessive scattering content or had the acoustic impedance of the sphere been too high, the far side of the sphere would have been in a shadow zone.

4. 3D rendering of image data

A feature of both microCT X-ray and volumetric phased-array ultrasound is the ability to render the volumes examined. Using MicroView [5] software the data from both the high frequency pulse-echo phased array ultrasound and CT scans were rendered and compared directly as illustrated in Figure 11.

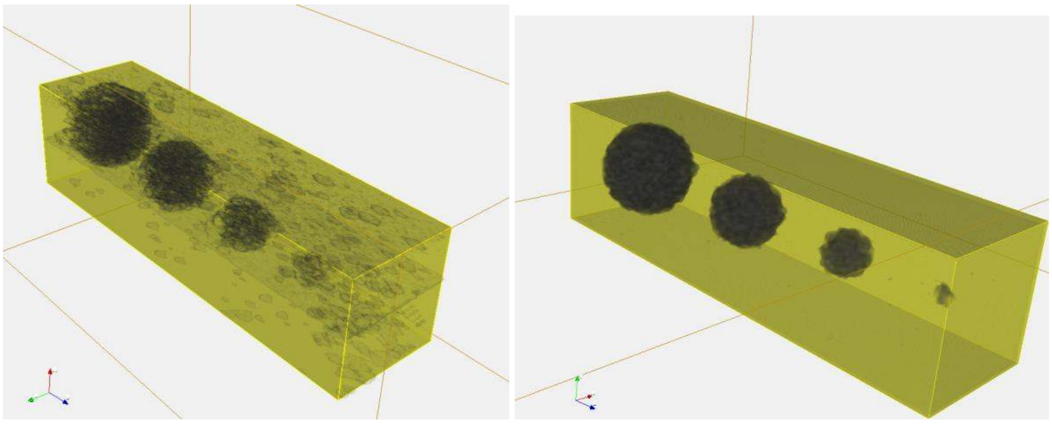

Figure 11 Phased-array ultrasound (left) and CT X-ray (right) data rendered for comparison of the 4 largest spheres

The phased-array rendered image appears to be noisier. This is partially due to the greater sensitivity of the ultrasound to the smaller voids and the region of weak laminar bonding at the mid-depth of the block.

5. Conclusions

A prototype phantom has been developed that can be used to verify imaging software for a variety of test modalities. In addition to the ability to compare ultrasound and X-ray data displays, the clear matrix allows for direct viewing confirmation of target placement and dimensions.

The prototype has been made with relatively small density differences between the matrix and targets to increase the challenges involved in resolving the target boundaries. Adjustments to the material properties can be made to increase or decrease the interface conditions seen by the examining method(s).

Close acoustic impedance matching of the targets to the matrix avoids shadowing effects of the targets in the ultrasonic images.

Close velocity matching of the targets to the matrix avoids image distortions in the ultrasonic imaging.

Rendering and data registration (overlaying the same volumes) can be used to compare differences and similarities between the data collected on the same sample using different modalities or systems.

Different target shapes, distributions and sizes are considered for future development.

6. Acknowledgements

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