

# RAPID DISTRIBUTED DATA COLLECTION AND PROCESSING WITH ARRAYS – THE NEXT STEP BEYOND FULL WAVEFORM CAPTURE

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## Abstract

Ultrasonic C-scanning is widely used for large area flaw detection but acquiring the full RF waveform for each surface point – Full Waveform Capture (FWC) - offers many advantages. A system that used phased arrays to achieve this without loss of area coverage rate has been reported [1]. FWC allows many signal processing operations, previously only possible at acquisition, to be performed off-line. Multiple or time-consuming algorithms can be performed on the same data set without compromising inspection speed but some must still be performed at acquisition.

Although ultrasonic arrays are now widely accepted in imaging systems, their full capability will only be realized when they are viewed as distributed data collection devices [2]. The acquisition of an RF dataset - corresponding to multiple combinations of transmit and receive locations along an array - is referred to as Full Raw Data (FRD) collection. The modular array hardware of DSL's *FlawInspecta* has been extended so that it can achieve this FRD acquisition at real-time rates. This capability significantly extends the range of post-processing operations that can now be performed, including: steering, aperture and focusing adjustments; data-dependent adaptive focusing; and multi-array data processing.

The extensive dataset is acquired and processed on-the-fly to yield images at real-time rates and so area inspection is still achievable. More sophisticated processing algorithms can be performed once the acquisition is complete or on archived data. A data storage format, based on the industry standard AVI format, has been chosen that is flexible enough to support a wide range of acquisition configurations. This format is being made available so as to provide an interface for end-users to develop customized algorithms.

There are many applications that can benefit from rapid acquisition and manipulation of FRD. One currently under investigation uses signal processing techniques for improved detection, characterizing and sizing of flaws by utilizing beams from different parts of the array to inspect the same flaw [3]. One processing option involves incoherent re-combination of the echoes from different beam paths. It is similar to the “compounding” technique widely used in the early days of medical ultrasound imaging to ensure the detection of specular targets that would otherwise reflect energy away from the transducer. Another option being investigated is coherent processing of the multi-path data for greatly enhanced resolution. These techniques are particularly suited to inspection within the layered structures prevalent in airframes.

The paper reports on the architecture of the data acquisition system and outlines how the distributed data is collected and processed on-the-fly at real-time rates. The tradeoffs between acquisition speed and post-processing capability are covered and used to illustrate the importance of a flexible, open source data storage format to allow end-users to develop customized applications. The range of post-processing

options is then outlined with reference to potential applications and the results of current work in progress, to offer enhanced flaw sizing, is presented as an example.

## 1. Introduction

It has been shown that Full Waveform Capture (FWC) can offer many benefits over conventional storage of gated data [1]. Many operations that would normally have to be carried out at acquisition time, such as adjustment of gate position, width, level and mode, can now be implemented as a post-processing on the FWC data. Other more sophisticated processing options, including interface-following gates, gate-to-gate ratios and spectral analysis [4], are also possible. Many applications involve inspection of an area and FWC provides a means for documenting and archiving the full 3D volume. The results can be presented as a C-scan mapping of a chosen parameter from a specified depth; a B-scan in any orientation; a 3D rendition; or indeed any custom projection according to the application.

The speed of acquisition is fundamental to the practicality of an NDT inspection, not merely because time costs money. Manual inspections are inevitably interactive and so require an apparently instantaneous response on the display as a probe is scanned over a defect. Rapid coverage is also essential to minimizing cost and downtime for automated inspections. The area coverage rate should only be constrained by the pulse repetition frequency (PRF) that, in turn, is limited by the velocity, attenuation and geometry of the target material. A practical FWC instrument should therefore be at least as fast as the equivalent system that acquires just a single value instead of the full waveform.

A prime purpose of NDT is to detect and classify anomalies. Although there is no such thing as a typical flaw, many are laminar and reflect energy in specific directions whilst others are better characterized by the way they scatter over a wide range of angles. In general there will be a combination of properties. For example, a laminar flaw will still produce wide angle scattering from the edges and it is this that forms the basis of the Time of Flight Diffraction (TOFD) measurement technique. Orientation dependent reflections will only be detected for specific combinations of transmitter and receiver locations and special pitch-catch techniques have been adopted to ensure that such targets are not missed [5]. It is possible that the angular response of the backscatter signal could be used to differentiate between flaw types in much the same way that it was used for early tissue characterization work for medical ultrasound [6].

Lab-based acquisition systems that record the RF data sequence from all combinations of elements of an array have been in use since the 1970s, particularly by the manufacturers of medical ultrasound systems, to assist in the development of phased array imaging systems and one such approach was also used for NDT [2]. Continuing improvements in size, cost and performance of acquisition and computing hardware means that this approach is becoming progressively more practical and the recent literature has described such a system [7]. However, it is slow and the authors acknowledge that the acquisition time of approximately 40 minutes for a single data set is a major limitation to its transfer to field use. They describe one specific application, termed total focusing method (TFM), that is primarily the extension to dynamic focusing on transmit. However, this is just one of many possible applications that could make use of the distributed data collection.

This new paper reports on the architecture of the data acquisition system and outlines how the distributed data is collected and processed on-the-fly at real-time rates. The tradeoffs between acquisition speed and post-processing capability are covered and used to illustrate the importance of a flexible, open source data storage format to allow end-users to develop customized applications. The range of post-processing options is then outlined with reference to potential applications.

## **2. Distributed Data Collection**

### **2.1 Aim**

The reason for acquiring distributed data is to allow post-processing operations that would otherwise be impossible and, by storing this data, the ability to perform this remotely or on archived data sets. The options include imaging enhancement operations, such as manipulation of the steer angle, focus and aperture shading, but these represent just a small subset of what is now possible. Multi-angle view (compounding), non-linear operations and scattering analysis are all possible and some applications are outlined.

### **2.2 Implementation**

The rapid FWC capability of the *FlawInspecta* from Diagnostic Sonar Ltd. (DSL) has been described elsewhere [1, 8] and, combined with the ability to manipulate the locations of transmit (Tx) and receive (Rx) aperture separately, makes this equipment particularly well-suited for Full Raw Data (FRD) collection. The hardware is modular and PC-based and so able to exploit the cost/performance tradeoffs of parallel acquisition channels as well as taking advantage of the continuous developments in processor and bus speed.

The number of Tx/Rx combinations is much larger than the number of transmissions required for a conventional phased array imager and so the acquisition rate will be significantly lower unless a careful optimization is performed. The FWC system was designed to handle data at rates far beyond the maximum PRF that the material properties allow and so the acquisition rate is constrained only by the application and not by the hardware. This factor is even more important for the FRD acquisition.

### **2.3 Constraints**

The existing FWC instrument can be configured to scan and acquire the full sequence of Tx/Rx combinations but this results in a reduction of acquisition speed. The constraints imposed, and the solutions adopted, are outlined below as they are key to ensuring that the technique transfers successfully from the lab into the field.

#### **2.3.1 Dynamic range considerations**

The small transmit area used in each FRD excitation means that the total beam energy is significantly less than that from a conventional array system. This is further compounded by the beam being much wider and so the energy arriving at a flaw, and hence being reflected back, is greatly reduced. The noise floor of the system and the digitizing resolution must be able to cope with this change. Although the noise on any single A-scan is now greater than in a conventional system, much of this is integrated out when the image is reconstructed from the much larger number of A-scans as long as the amplitude resolution is fine enough to preserve the noise characteristics. However, particular care has to be taken when the instrument is operated close to sources of electrical interference (e.g. welders).

The maximum signal handling capability is also an issue. There must be no signal saturation in the FRD A-scans if their summation is to mimic the beamforming of a conventional phased array system, assuming that the acoustic propagation in the latter is operating in the linear regime. This can be a major problem for inspection geometries or configurations that have a major reflector at a different angle from the steer angle. For example in shear wave weld inspection, the array will receive strong echoes (and repeats) from the back wall of the plate. With a normal phased array beamformer, the transmit steering ensures that minimal energy is sent in this direction and the same cancellation will take place during FRD reconstruction but only as long as these unwanted echoes do not saturate. One option that is supported by the hardware is to do a weak transmit steer by using a small group of elements on transmit rather than a

single element. One of the most effective approaches is to use a pair of elements phased so as to destructively cancel in the direction of the unwanted echoes.

### 2.3.2 PRF and scan sequence considerations

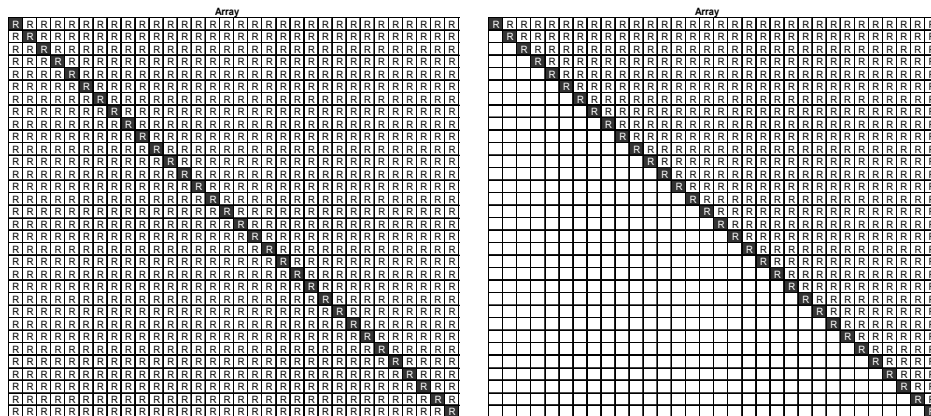
In the ultimate system, the PRF is only constrained by the physics of the target and acoustic delay line. The material velocities and the delay line length determine the time from transmit to the acquisition of the furthest relevant echo. The attenuation and geometry of the materials define the additional delay required before the next excitation to allow the echoes from the previous pulse to decay to an insignificant level. Unlike a mechanically scanned probe, the beams from a phased array can be considered to have zero inertia and so can be scanned in any sequence. If sequential beams are sufficiently well separated, so that there is minimal spatial overlap of the beams, then this additional delay can be minimized. This property has been used to maximize the PRF by scanning in an interlaced sequence [8].

The wide beam angle produced in distributed data collection means that interlacing to optimize the PRF is much less beneficial. Instead, it is more important to ensure phase coherence between the individual Tx/Rx sets that will contribute to the final image – especially when the probe head is moving over the surface to scan an area – and the scan sequence is therefore chosen to optimize this coherence.

### 2.3.3 Frame rate considerations

The sum of all the individual RF A-scans that make up an FRD data set is referred to as a frame. It is very desirable to maximize the frame rate as this determines how quickly an array can be scanned over a surface to inspect a volume as well as ensuring a real-time response time when the operator is using a B-scan to search for flaws. There are several approaches that can be used to optimize the frame rate.

The frame rate is the PRF divided by the number of pulses assuming that the manipulation (reformatting and display) of the data does not add any overhead. The PRF is limited by the physical constraints as described above and so the number of pulses remains the only parameter under operator control. If, as is normal, the transmit aperture is just one element (or in general has the same aperture and phasing on transmit as receive) then reciprocity means that almost 50% of the available combinations can be eliminated. This because a transmission, centered on element M with receive on element N, is equivalent to a transmission centered on element N with receive on element M so only one of the pair needs to be acquired. Figure 1 tabulates the combinations of Tx (shaded box) and Rx (R) need for full acquisition and for the reduced data set by taking advantage of this reciprocity.



**Figure 1. FRD sequence for full acquisition (left) and for reduced data set (right)**

Another way to minimize the number of pulses is to restrict the maximum separation between transmit and receive elements if it is acceptable to limit the maximum reconstruction aperture. For example,

accepting a restriction of the maximum reconstruction aperture to 50% of the array length would reduce the number of combinations required, as shown in Figure 2, and would give almost a further doubling of acquisition rate.

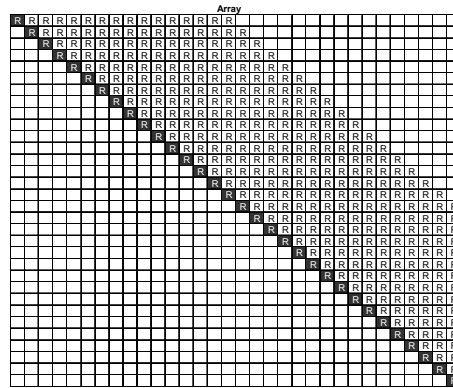


Figure 2. FRD sequence where reconstruction aperture can be restricted.

If the frame rate is still too slow after all these optimizations, it can be improved by increasing the level of parallelism on the number of receive acquisition channels at the expense of system cost. Figure 3 shows the actual pulse sequences where the acquisition parallelism covers 50% and 100% of the reconstruction aperture respectively. The speed bottleneck then moves to the transfer rate of the system bus but even this is becoming less of a constraint with the advent of the PCI Express bus. The ultimate system has sufficient on-board memory to buffer the full acquisition of the associated channels with bus transfer taking place at the end of the scan.

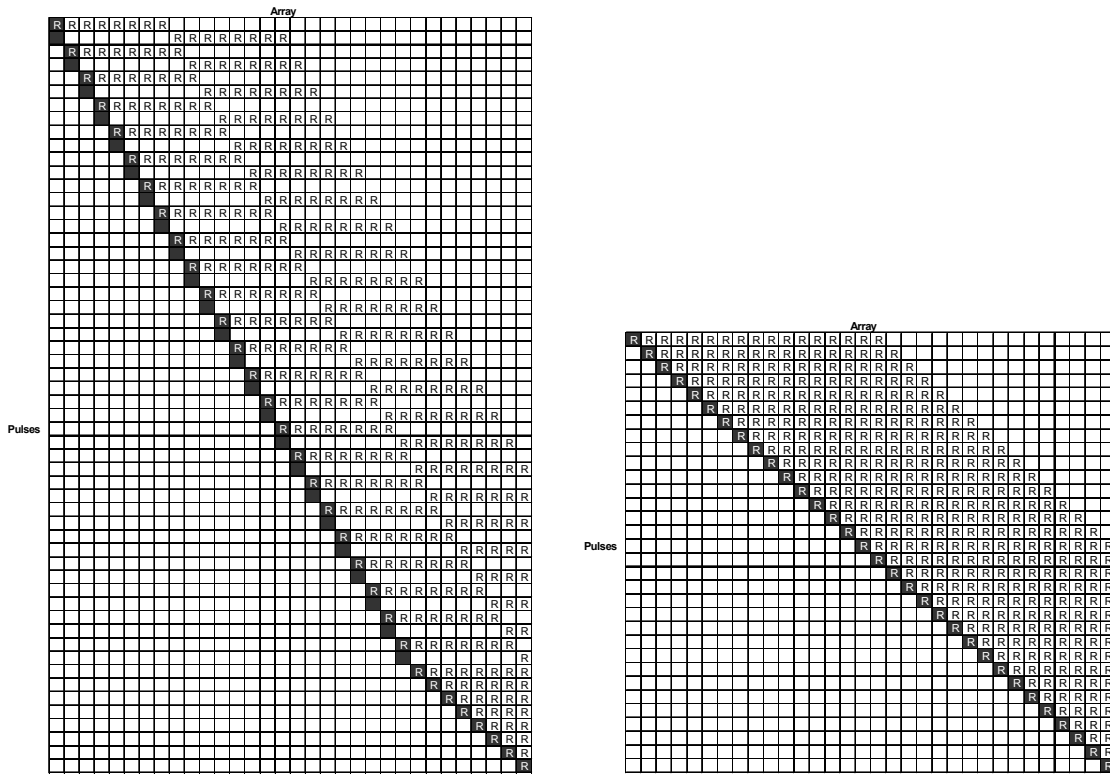


Figure 3. Pulse sequence for 50% (left) and 100% (right) acquisition parallelism.

## **2.4 Acquisition rates**

A typical case of a 64 element 5MHz 67mm array on a carbon fiber composite specimen with a maximum reconstruction aperture of 33mm would be able to acquire the full FRD frame in 208 pulses for 8 parallel channels on receive. The FRD frame rate for a 20 kHz PRF would therefore still be as high as 96Hz. The scan sequence is chosen to minimize the time between signals that will be coherently combined, so that the potential defocusing effects during a volume scan are also minimized. Some inspection geometries and materials will require the use of lower PRFs, for example where the array is mounted on an angled wedge for best generation of the shear wave inspection angles for weld inspection, and these applications will either need to have the highest level of parallelism or accept a reduction in the scan rate.

Reconstruction of the data places a demand on the system processor(s) and it is important that this doesn't detract from acquisition speed. With so many different reconstruction options, it is difficult to optimize the speed of every algorithm. As a result, the approach adopted has been to use a restricted range of reconstruction algorithms during acquisition so as to provide immediate feedback that the data being acquired is of high quality – i.e. that there has been adequate coupling throughout the volume scan. Once the acquisition scan is complete, or during pauses between scans, the more sophisticated algorithms can be re-run on the same data set.

## **2.5 Data storage formats**

The generic nature of the FRD data set means that there would be considerable benefit in making the data storage format available so that end-users can write their own application specific algorithms. The format has to be flexible enough to support the reduced scan size acquisition configurations that may be chosen to optimize the frame rate whilst still managing to handle distributed data collection between multiple arrays. Although reconstruction speed is generally less important than acquisition speed, it should not be ignored as a rapid response to operator interaction produces very favorable user responses.

The acquisition beam sequence is optimized for the type of scan (whether interactive B-scan or area coverage with C-scan display) taking into account the PRF and the level of hardware parallelism fitted. When the scan is complete, or even during pauses between scans, the data is reformatted into a standardized sequence for saving and the full reconstruction algorithms are used to update any images. The scan format for the data is the industry standard AVI format that has been used successfully for recording the FWC data over the target area. Each frame of the AVI corresponds to an ultrasonic frame at the associated location and so the AVI sequence represents a volume scan as a stacked set of frames. Since each FWC frame is effectively an RF B-scan, an advantage of the AVI file format is that the replay (using any standard reviewer such as Windows® Media Player) is equivalent to a B-scan sweep through the structure.

The same approach is used for FRD except that the frame no longer has a 1:1 correspondence with the RF B-scan. The exact beam sequence, along with other relevant information, such as the transmit aperture and focusing should there be any, is saved into a configuration file. The file also includes full details of the array element size, position and orientations in 3 dimensions. End users, who wish to develop customized algorithms, can use this configuration file as a way to extract the data from the associate AVI data file.

## **2.6 Potential applications for FRD**

There are many potential applications that would benefit from processing an FRD data set. At one extreme is the ability to perform minor adjustment to the focus as a post-processing. An example of such a scenario is where a technician acquires the data that is then processed and analyzed remotely or by a

more experienced specialist, in much the same way that FWC extends the range of options over conventional inspection. Other possibilities - which are by no means exhaustive – are outlined below.

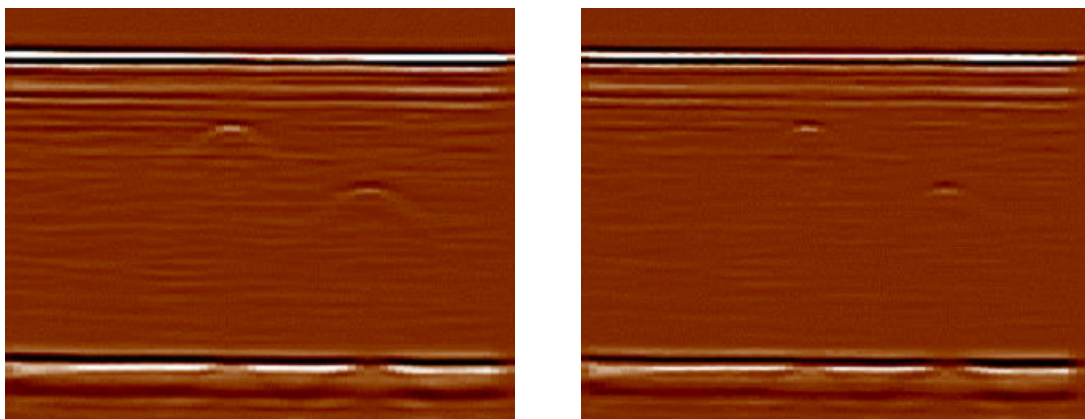
### **2.6.1 Optimized imaging**

Dynamic focus on receive has been available on medical ultrasound array systems since the mid 1970s [9]. The transmit beam can only have one focus and so the only way to achieve any measure of dynamic focus on transmit was by building up the acoustic beam from a sequence of transmit zones, although at the expense of frame rate. This capability, of multi-zoned transmit and dynamic receive focus, was available on DSL's *FlawImager* NDT array scanner introduced in 1978.

Reconstruction of the FRD data set into an image can mimic the dynamic focus operation. However, there is no longer any constraint on the transmit focusing and so every point in the final image is dynamically focused on transmit as well as on receive. The benefits of aperture shading are well known for controlling array sidelobes, at the expense of the width of the main beam, but it requires extra cost and complexity in hardware. This is easily applied on the FRD data set and there is now the option of choosing whether to maximize the aperture for enhanced resolution or to implement shading for optimized suppression of image anomalies. The element directivity response will determine which elements will have a valid contribution for any given image point. The *FlawInspecta* addresses this by allowing the operator to define the aperture as an F-number and so the number of elements contributing increases linearly with pixel range.

### **2.6.2 Non-linear processing**

One of the advantages of access to the FRD data set is the potential to perform non-linear processing operations. Standard beamforming involves linear summation of the phased aligned Tx/Rx combinations but with the FRD data set it is possible to combine these in other ways. One technique – multiplicative processing – takes the log of the signal before summation and then anti-logs the result, producing a reduction in the beam width. It was originally tried for medical imaging but was not adopted because of the artifacts produced from the diffuse reflectors. However, NDT applications that involve the detection and characterization of isolated defects – i.e. where there should be no echoes - could benefit from this enhanced resolution. The RF images of side-drilled holes in Carbon Fiber Composite (CFC) shown in Figure 4 demonstrate the resolution enhancement achieved by non-linear processing. The 5MHz images were acquired with the relatively small aperture of 6mm.

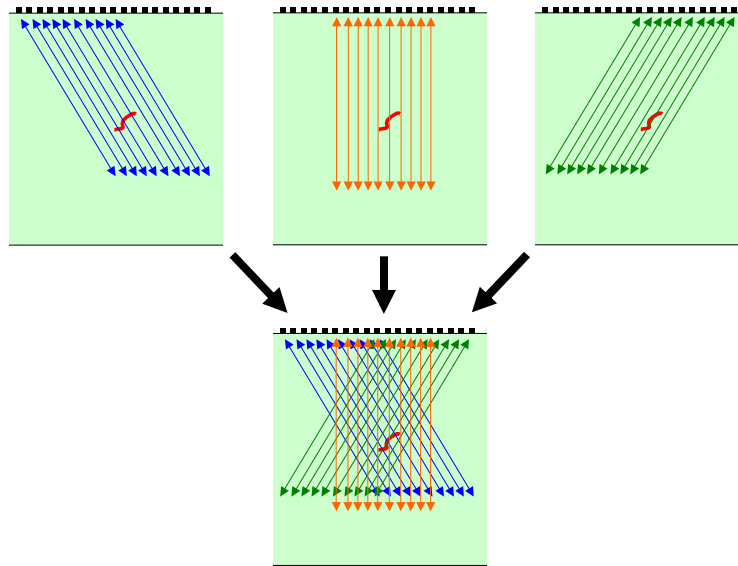


**Figure 4. RF images of holes with standard (left) and non-linear (right) processing.**

### **2.6.3 Compounding.**

Medical imaging has long made use of a technique, termed compounding, that enhances the visualization of a target by combining views from different directions. It was commonly used in gantry scanned

systems where the probe was rocked to and fro during the manual scan over the patient and each target pixel held the maximum value obtained from any scan passing through it [10]. One of the benefits was to ensure that the full extent of curved specular reflectors, such as the fetal skull, was recorded. This was particularly important where the dynamic range of the system was insufficient to fill in the structure and is equally applicable to NDT data, as shown in Figure 5. Another benefit reported was the improved resolution obtained when echoes from substantially different directions are superimposed and a variation of this approach has been assessed on the FRD data set [3]. Compounding has always been a combination of incoherent data from the different views but access to the FRD data set means that coherent recombination is also possible.



**Figure 5. Compounding – the data fusion of views from the same array.**

The advent of real-time imagers with extended dynamic range and display compression saw the demise of compounding. However, its popularity has been revived over the last few years due to the use of arrays with finer pitch that allow this combination of views and the benefits that are seen with reduction of the speckle that is associated with the coherent imaging. An FRD data set permits user-configurable compounding as a post-processing option for NDT.

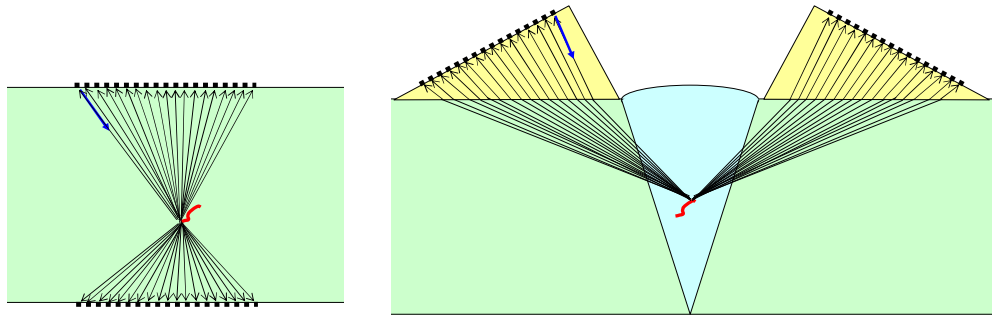
#### ***2.6.4 Target-dependent processing.***

A conventional phased array system requires that the element focusing terms are known before the inspection and whilst these can be derived, or pre-calculated, for known target geometries, there will be cases when the inspection is being performed on unknown complex structures. The FRD data set provides a means for measuring the surface layer structure and using this information to derive optimized focusing for the next layer down and so on for complicated structures. It is also well suited to adaptive cancellation of repeat echoes within the multi-layered composite structures that are now becoming common, particularly for aerospace. The use of FRD for these adaptive techniques becomes even more important when the target geometry changes over the scan area – a common occurrence in aerospace inspections where there is a progressive thinning of the sections along the aerofoil length.

#### ***2.6.5 Complex/Multiple array processing.***

Although dynamic focusing has been available for many years, even for NDT imagers, it has recently become more popular due to the greater acceptance of phased arrays. Care has to be taken with the

extrapolation of the impressive results on side-drilled holes to the real-world where the fixed focus of the scan plane thickness is flattered by the cylindrical geometry of the side-drilled holes. The only way that the same performance can be extended to the slice thickness direction is by the use of dynamic focus with 2D arrays. The FRD approach is equally applicable to 2D arrays by merely recording the relative positions of the elements in 3 dimensions. Multiple arrays, whether on the same or opposite inspection surfaces, can also be handled as an extension to the single array case.

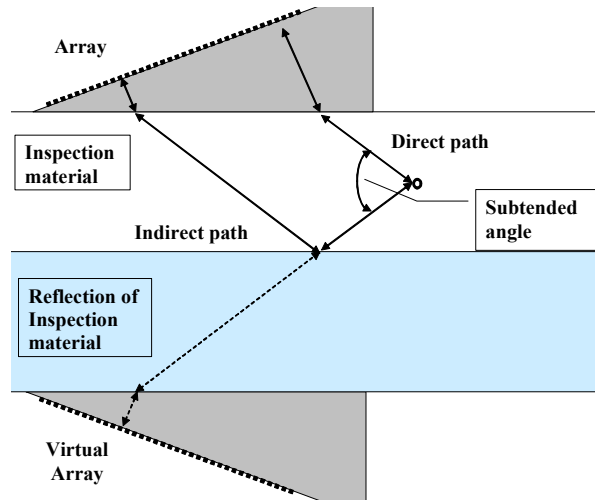


**Figure 6. Multi-array configurations combine pulse-echo with thru-transmission (left) and pitch-catch (right).**

Some work has been performed with arrays on opposing surfaces as shown in Figure 6 (left). Not only does this combine imaging views from top surface, bottom surface and through-transmission but the FRD data set also offers a greatly increased angular coverage for scattering analysis. Preliminary results have proved promising and will be published separately. Similar benefits are seen with the arrays in a pitch-catch configuration as shown in Figure 6 (right).

### 2.6.6 Virtual array processing.

A variant of the multi-array technique makes use of the Virtual Array produced by a reflection in the target medium. The layered structures commonly found in aerospace applications are particularly suited to this and Figure 7 shows the virtual array produced.



**Figure 7. Virtual Array produced in layered media.**

Measurement from the direct echoes of the crack size and orientation can be very difficult, even from an image, for some crack orientations. However, the indirect path echoes can be processed by a simple

reflection operation and result in much easier measurements from the intersection points, as illustrated in Figure 8.

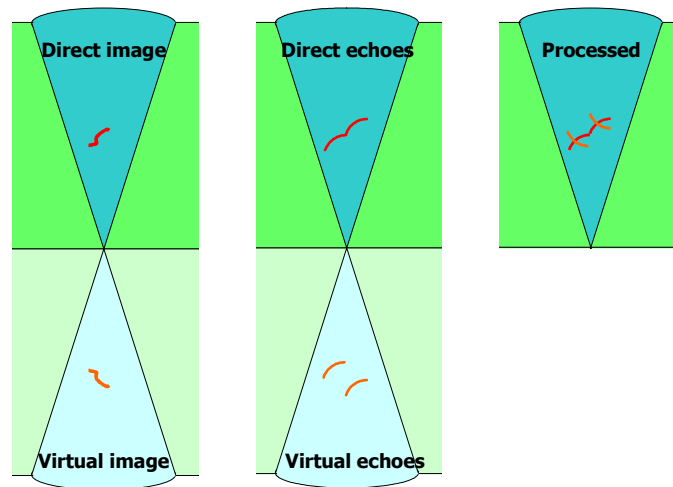


Figure 8. Compound processing of echoes from direct and indirect paths.

The results with real data on a test block [3] are shown in Figure 9. The left hand image shows the echo pattern from 5 test holes. The dotted line marks the position of the reflective surface - the echoes above it are direct and those below are virtual echoes. The right hand image shows the processed result after reflecting the virtual image back onto the direct image. The intersecting arcs make any measurements much less susceptible to error.

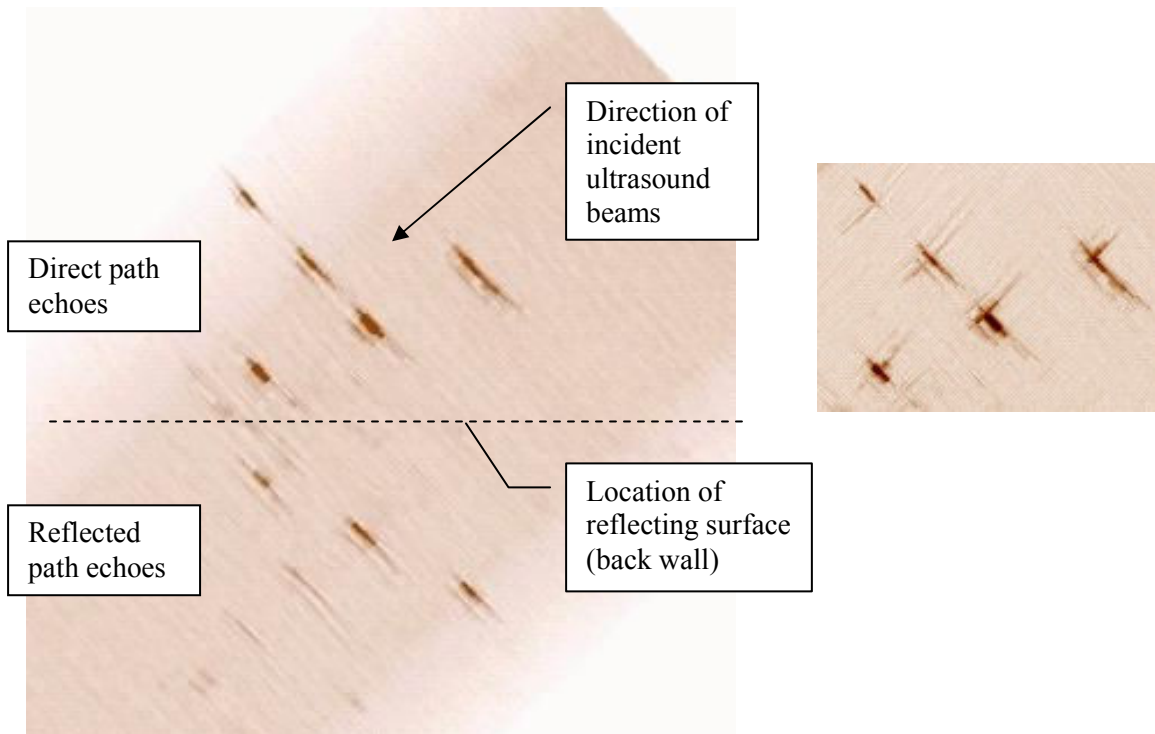


Figure 9. Real and virtual image (left) and compound processed result (right).

### 3. Conclusions

Full Raw Data collection and processing has been introduced as the next natural evolutionary step after Full Waveform Capture and some of the many additional advantages have been outlined. The approach would remain a lab-based technique unless the acquisition can be achieved at similar rates to conventional inspection.

The constraints on the acquisition have been reviewed and the modular hardware of the commercially-available *FlawInspecta* has been adapted to address these requirements at a suitable speed. The data sets are acquired at real-time rates and reconstruction of B-scans and C-scans are performed on-the-fly to ensure maximum operator friendliness as well as extending the technique to area coverage.

The separation of acquisition from processing offers the possibility for application specific processing and a flexible data storage format, that will be made open source, will allow end users to develop their own algorithms. A number of potential applications have been outlined and several are already under investigation with promising results that will be reported elsewhere.

### Acknowledgements

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