Real-time full matrix capture + total focusing and other novel imaging options using general purpose PC-based array instrumentation

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Data acquisition using full matrix capture (FMC) and image reconstruction by the total focusing method (TFM) offers many benefits over conventional ultrasonic array beamforming techniques. These include dynamic focus on both transmit and receive for enhanced resolution and the ability to alter the focus and steer angle without re-scanning. However, the technique has remained in the laboratory because of the costs associated with acquiring many channels in parallel and the absence of a real-time reconstruction capability. This paper describes a solution to these constraints. The paper reviews the issues limiting the current implementations and describes how they were overcome by using flexible and scalable PC-based hardware modules. This new architecture already achieves acquisition and processing at 20 Hz and higher, meeting the requirements for interactive scanning and so enabling these techniques to transfer from the laboratory into the field.

Results from the first phase of a continuing investigation are presented. New application approaches, where these techniques offer particular benefits over conventional techniques, are discussed.

1. Introduction

Ultrasonic phased array imaging has been used in NDT for over 30 years, but the increased cost and complexity over conventional techniques means that it is only in the last decade that it has become widely accepted. Although medical ultrasound was derived from NDT in the 1950s, the much larger medical market has been a significant driving force and as a result many of the imaging innovations, especially with phased arrays, have come from this field. The technology transfer has therefore been largely one way. Conventional array imaging involves sending appropriately phased excitations to a group of elements so as to create a focused transmission beam in a defined direction. This mimics a similarly-sized conventional probe but with electronically-controlled focus and direction properties. The same approach is used on receive but with the added advantage that the inter-element delays can be changed with time so that the focus tracks the propagating wavefront, a technique known as dynamic focusing.

Scanning is achieved by steering the beams through an arc or by stepping the transmit and receive apertures along the length of the array. This results in a good signal-to-noise ratio, which is essential for medical imaging due to the strong frequency-dependent attenuation in tissue. The main disadvantage is that the transmit focus is fixed and so the aperture has to be reduced to extend the depth of field, but this also limits the lateral resolution. Some improvement can be achieved by multiple transmissions in the same direction, each with a different focus, and the resulting beam is made up from appropriate range segments from each pulse. This multi-zone transmission mode reduces the loss in resolution but care has to be taken to ensure smooth transitions in beam profile between each of the transmit zones. It also drops the overall imaging frame rate and can produce zone artefacts from repeat echoes in low attenuation structures – both of which are major constraints for area-scan NDT systems.

An alternative approach was used to investigate focusing strategies for in-vitro medical imaging to try to compensate for structures with differing acoustic velocities. Each element is excited individually and the RF A-scan from each receive element recorded. This is repeated for every combination of transmit and receive element position. Each pixel in the reconstructed image is made from the weighted sum of the appropriate sample from each RF stream. The round trip transit time from the transmit element to the pixel and back to the receive element is used to select this sample. One benefit of this process – termed full raw data (FRD) acquisition and processing – is that every pixel is optimally focused on transmit as well as on receive. The reconstruction transmit aperture can therefore be as large as the element directivity profile permits for yet further improvement in resolution.

This approach was extended to the NDT field at the end of the 1970s. However, the reconstruction uses significant processing power and this was a major constraint with the hardware available at the time, shown in Figure 1(a), which used a Z80 processor clocked at 40 MHz. It therefore took around 2 h to produce the reconstructed image, shown in Figure 1(b), of 1.5 mm side-drilled holes in a steel test-piece using a 64-element 2 MHz array, shown in Figure 1(c). The key feature to note is the resolution, since the image shows the left-hand holes of the middle row (at 165 mm range) as separate features, even though the centres are only two wavelengths apart.

The acquisition on this early imager was only a single channel at 8 bits, which was multiplexed through all combinations of transmit and receive elements. A 64-element array required 64 × 64 = 4096 pulses and so was much slower than a conventional imager. Although useful for evaluating reconstruction algorithms, the slow acquisition and processing speeds ensured that this would be for laboratory use only.

Component integration, acquisition performance and processing power have all greatly increased and the approach has been examined afresh. Several papers have reported on this with the first referring to the acquisition as full matrix capture (FMC) and the processing as the total focusing method (TFM). The speed issues that are critical when scanning were addressed in, including techniques for acquiring subsets of the data without degrading imaging performance based on a priori knowledge of the way the data would be processed. It also described extensions, where more than one element is excited at a time so as to improve the dynamic range.
2.1.2 Data rate reductions

In conventional ultrasound imaging systems, the echo signals from each element are combined into a single stream of data samples representing the focused receive beam. This process is referred to as receive beamforming and there are various hardware approaches in which the multichannel serial streams can be merged:

- Custom application specific integrated circuits (ASICs) offer the highest performance but are both inflexible and expensive to design. They are therefore only appropriate for mass production, where the design costs can be spread over a very large number of systems.
- Digital signal processors (DSPs) are used in medical ultrasound imagers but primarily for back-end use on the beamformed data. They are best suited to complex processing operations on a limited number of channels whilst the beamformer implements relatively simple algorithms on many.
- Graphics processor units (GPUs) are special case multicore DSPs optimised for high data throughput for displays and offer considerable processing power at relatively low cost because of the size of the PC market. However, if conventional graphics cards are to be used to take advantage of the mass market price, there will still be the issue of data bottlenecks across the system bus.
- Field programmable gate arrays (FPGAs) are hardware devices containing a massive matrix of low-level logic blocks, each with a functionality customised by a bit pattern in an overlay memory. The links between each block are also configurable and so the result is a large digital hardware resource similar to ASICs but with the advantage of programmability. The hardware blocks run in parallel and so it is easy to implement the multichannel processing for array imaging. Most high-performance FPGAs have inputs with de-serialising capability so can receive data directly from the AFE devices and many now also contain multiple DSPs so combine the benefits of these as well.

2.2 Hardware implementation

FPGAs therefore offer a flexible route to acquire and process the data directly from AFES and indeed are widely used for this purpose in commercial scanning systems. Several manufacturers provide FPGA boards for PC platforms, but the hardware is just one consideration. Another significant challenge of using FPGAs is that they are typically programmed using a hardware description language (HDL), such as VHDL. Programming a system with VHDL can be very time consuming, lengthening project timelines. However, recent advances in development tools have made FPGA programming more efficient by allowing higher-level graphical tools to be used for overall system design, which can also leverage existing VHDL IP (Xilinx CORE Generator™, in-house developed, third party, etc) where appropriate. When used properly, these tools can enable the very fast development of a system so that algorithms data streaming. However, data buffering will be needed before any transfer across the system bus.

Interconnect constraints are another key consideration. If the digitised data is passed between devices as parallel data streams, then 32 channels at 12 bits would require 384 tracks in parallel, all clocking at 50 MHz or higher. This is not practical so data transfer must use synchronously clocked serial streams and many of the current generation of multichannel ADCs now use this approach. The relentless pressure to reduce the size and cost of medical imagers has driven component manufacturers to integrate much of the circuitry between probe and digitiser. Many now offer preamplifiers, filters, variable gain amplifiers and ADCs for eight or more channels in the same device, referred to as ultrasound analogue front ends (AFE)s. All use the same serial interconnect standard to transmit the data and so any processor will need to have a matching receive interface.

Further enhancements to the FRD technique were described in[6], emphasising the wide range of post-processing options that become possible, including multiple steer angles and compensating for multiple velocities in anisotropic materials[6] with 2D arrays.

Whether the goal is to improve the imaging performance or to use one of these novel post-processing operations, the limited acquisition and processing speed has remained a major constraint in moving the techniques from the laboratory into field trials. One common approach to address speed issues is to customise the hardware, but this tends to limit the flexibility that is one of the benefits of this type of imaging. This paper describes an approach using PC-based hardware and software that achieves the desired speed increase whilst retaining flexibility. It is both modular and scalable, so well-suited to address future requirements such as the increased channel requirements of 2D arrays.

2. Modular architecture

The following section discusses the challenges and outlines how the approach using field programmable gate arrays (FPGAs) is able to overcome these constraints without compromising the goals of scalability and flexibility. Some early results of acquisition from a test-block are then shown, where the reconstructions illustrate the benefits of post-processing. These techniques open up a wide range of new inspection options and some examples of these are then presented.

2.1 Hardware approach

The combination of sampling rate, data resolution and channel count produces a data rate that greatly exceeds the backplane bus speeds of PCI and even PCI Express. Some level of data rate reduction is therefore needed before transfer across the system bus.

2.1.1 Data rate and connectivity considerations

Ultrasound array systems typically sample each channel at 50 MHz or higher. 12-bit sampling is adequate if variable gain amplification is applied before the analogue-to-digital converters (ADCs) but this produces a total data rate of 3.2 GB/s for 32 channels at 50 MHz. PCI Express Gen1 can handle 250 MB/s per lane and, whilst this rises to 500 MB/s and 1 GB/s per lane for Gen2 and Gen3, respectively, it is clear that raw data streaming of all channels will push current technology to the limit. Pulse-echo imagers acquire data in bursts, producing some reduction compared to sustained
and hardware performance can be evaluated and refined.

For the results discussed in this paper, the hardware used was National Instruments (NI) FlexRIO FPGA modules programmed with the NI LabVIEW FPGA module, a graphical design language that can be used to design FPGA circuitry without needing to know VHDL coding. NI FlexRIO combines interchangeable, customisable I/O adapter modules with a user-programmable FPGA module in a PXI or PXI Express chassis. The Virtex series of Xilinx FPGAs are used on the board to achieve high I/O and signal processing performance. The NI FlexRIO hardware includes infrastructure components for I/O connectivity, PCI Express bus interfacing and DRAM communication.

### 2.2.1 PXI implementation

The FlexRIO family is available in either PXI or PXI Express formats. PXI (or PCI eXtensions for Instrumentation) supports all standard PCI functionality and also includes clocking and a trigger bus between cards for real-time synchronising\(^{36}\). PXI Express is the PCI Express equivalent and the FlexRIO Express cards offer enhanced synchronising and direct board-to-board data streaming. As mentioned above, the I/O interface for FlexRIO is through interchangeable adapter modules that have direct access to the FPGA pins for maximum interface speeds. One such module (the NI5752) contains four eight-channel AFEs providing 32-channel 12-bit sampling with swept gain amplification. It also has 16 digital outputs and two digital inputs. Figure 2 (left) shows the adapter module fitted onto a FlexRIO express card.

The 16 digital outputs were used to control an existing 32-channel multiplexed pulser module. This can be used with a high-voltage power supply, transmit/receive protection switches and appropriate software to form a 32-channel FRD acquisition and processing system. The multiplexing can be extended to operate on receive as well, so a system for 128 or more elements can be implemented using just two PXI slots, as shown in Figure 2 (centre). Conventional imaging requires multiple independent pulser units operating in parallel and so an additional FlexRIO card is used for this case with a separate 32-channel pulser adapter module. This module was a custom development using the same FlexRIO FPGA module, but designing the pulser I/O with the FlexRIO Adapter Module Development Kit (MDK). As shown in Figure 2 (right), combinations of these three basic PXI slot modules (32-channel pulser module, high-voltage PSU + 32-channel Tx/Rx switches and pre-amps, and 32-channel digitiser module) with stackable multiplexer modules can be used to scale to any desired system configuration\(^{36}\).

**Figure 2. Modular implementation: FPGA card with digitiser (left); PXI chassis using two slots for FRD imaging system (centre); Used in generic 32-channel configuration with multiplexers, pulser and receivers (right)**

### 2.2.2 Integration with scanning systems

The safety critical parts of many structures require 100% inspection and this is driving the need for automated, or semi-automated, scanning systems. This used to be carried out by conventional single-element transducers operated in immersion or water-jet coupled scanning gantries. The pulse repetition frequency (PRF) was typically 1 to 20 kHz and so it was relatively easy to acquire at the instant that the scanning mechanics reached the correct location. With ultrasonic arrays, the PRF is similar but the image frame rate is around two orders of magnitude slower due to the number of image beams, complicating the synchronising between ultrasound data and mechanical positioning.

The rapid and predictable response time of the FPGA-controlled hardware means that the acquisition can be triggered by external events to produce a ‘scan-on-demand’ capability. It is therefore easy to achieve the maximum inspection speed for automated systems as well as accommodating the variable scan rates that occur with manually-driven inspections. The FRD approach can produce a complete image from fewer pulses than conventional imaging with focused transmissions and so has the potential to increase inspection speed further. The scalable nature of the hardware modules allows sufficient levels of parallelism on receive to accomplish this.

The recent, very rapid growth in the use of composites in both military and commercial aircraft is placing great demands on the inspection process. The current approach of inspecting large area components in customised gantry systems and smaller components by hand can no longer achieve the required throughput. Multi-axis robotic inspection systems, such as that shown in Figure 3, have the flexibility to address the mechanical scanning of these complicated parts. The array can be scanned over the component or the component moved through a fixed array’s scan plane. This flexibility is further enhanced by the post-processing options offered by the FRD approach.

**Figure 3. Robotic automated ultrasonic inspection**

The 32-channel FRD configuration discussed above was used to acquire FRD data from a steel test-block with 1 mm-diameter side-drilled holes and to reconstruct images from that data. Figure 4 (top) shows the pattern of holes (left) and the imaging geometry (right). The 32-element 1.5 mm pitch 3.5 MHz array was directly coupled onto the inspection surface and the first hole is 25 mm from the array.

The acquisition was performed with a single element pulsing and so the FRD frame is equivalent to FMC data. The firmware within the FPGA performs the 32 transmissions, storing the 32 RF A-scans for each into the high-speed DRAM on the FlexRIO. Once acquisition is complete, the host program on the PC requests a transfer of the full frame from the DRAM and then reconstructs an image. Here, a standard FlexRIO (NI’s PXI-7953R) was used in a...
2.4.2 Adaptive steering

This retrospective steering technique can also be exploited where the desired beam angle and start point is not known at inspection time. A common aerospace inspection is of the bonding between the outer carbon fibre-reinforced plastic (CFRP) skin and the inner stiffening spars. In the absence of any fasteners penetrating both components, the location of the spar will not be evident from the outside.

Figure 5. Beam steering by post-processing on same acquired data: FRD reconstructions on Figure 4 data at 0º (left), –20º (centre) and +20º (right)

The prime requirement is to inspect the bond between skin and spar, which can be done with 0º beams as shown in Figure 6 (left). Conventional real-time imaging allows the operator to move the array over the outer surface to locate the spar and then guide the scan along the length of the spar. In addition to the bond quality, the 0º beams can also find delaminations parallel to the surface in both skin and spar. However, it is desirable to extend this inspection to the curved triangular fillet region – sometimes referred to as the ‘noodle area’ – at the head of the T-shaped spar. The curved profile requires continuously varying inspection angles to interrogate the ply layers with a perpendicular beam for optimal detection. This angular range is produced by conventional sector imaging but the array would need to be translated across the surface to inspect each point at the matching angle.

Figure 6. Fillet inspection: initial reconstruction (left) at 0º detects disbonds and also locates spar position for generating beams to inspect fillet curves (right)

The ideal is to create a pair of virtual sectors, each positioned at the centre of curvature, as shown in Figure 6 (right). Potentially, this could be accomplished by a customised scan sequence with a conventional imager, comprising the linear sequence of 0º beams and then the beams of the virtual sectors. However, the positioning of the latter would need to be altered unless the image from the 0º beams is used to adjust the array position. Even then, it would suffer from reduced inspection speed due to the extra beams and assumes that the profile remains constant. An FRD system could create the virtual sectors without any additional acquisition time and automate the positioning, based on the measured contour, and so adapt to changing profiles. The choice of whether to do the processing on the fly, or on saved data as an offline post-processing operation, is then just down to scan speed requirements.

2.4.3 Adaptive imaging – Interface compensation and aberration correction

The ideal inspection set-up has the geometry known before the inspection, but this assumes that it has been manufactured correctly – something that the inspection may be attempting to verify. Conventional imagers could have a set of delay laws pre-configured to provide optimum focusing for a known geometry, such as through one or more interfaces. Any deviation from this idealised geometry will cause defocusing.
The FRD approach has no need for this *a priori* information. Each FRD frame is acquired as normal and the first reconstruction is performed, based on the best known information. In the example of an immersion inspection, shown in Figure 7 (left), the location of the interface is unknown so the first reconstruction is performed using the water velocity. This produces an accurate location of the interface, though everything beyond will be out of focus. Revised focusing laws are then created based on the measured interface and are used to correct the focusing within the material, as shown in Figure 7 (right). A multilayered structure would have the next interface accurately identified in this revised image, and the process is then repeated for each layer.

This approach can adapt to changing profiles during an area inspection of the component as for the adaptive steering. Again, if the goal is to image within the structure at a particular orientation, such as perpendicular to the CFRP plies, then the revised focusing laws can create this. If anomalies are detected, such as out-of-plane ply waviness, then there is the potential to adapt to this for an improved visualisation and therefore measurement of the anomaly.

**2.4.4 Adaptive scanning – ULTRAfast imaging**

This scanning mode aims to offer the fastest possible inspection speeds combined with the performance of FMC+TFM. The hardware must support multiple acquisition modes, including both high-speed parallel beamforming as well as FMC. There must be local processing within the data acquisition hardware with a rapid and predictable response time. It must also have fast data streaming with local buffering of data, such as via PXI Express bus into RAID storage hardware. All of these are addressed by the FPGA-based acquisition hardware, which provides very rapid and deterministic response times for decisions which can be made on the data as it is streamed through the acquisition card.

The ‘ULTRAfast’ scanning involves repeated acquisition of the data into the on-board DRAM with local processing being performed in parallel. Each image is monitored for potentially relevant data by a decision algorithm in the FPGA, with a relatively conservative threshold to ensure nothing relevant is missed. When the decision threshold is exceeded, the buffer data is streamed into the RAID and an alert sent to the scanning system in case the quantity of data requires a drop in scan speed.

One possible application area is the inspection of fasteners for cracking using an angled array to produce a shear wave within the layers⁶⁹. Figure 8 (left) shows the array being scanned over a strip of fasteners and the pre-processing within the FPGA detects the presence of the fastener from the echo data and streams the FMC data to disk for these regions of interest. One post-processing operation would use standard FRD reconstruction to identify potential radial cracks (centre) followed by matched angle beams (right) perpendicular to the radial crack to produce a normalised echo response.

![Figure 7. Adaptive imaging through interfaces: initial reconstruction (left) measures the position of the interface, which allows optimised focusing beyond (right). This process is then repeated for subsequent interfaces.](image1)

**3. Conclusions**

The paper has reviewed the benefits of full matrix capture + total focused and the related FRD imaging, and has identified cost, complexity and processing time as key factors preventing the technique from transitioning from the laboratory into the field. These constraints were then reviewed and FPGAs proposed as a powerful but flexible solution, combining the multichannel interface to arrays with the localised processing for data reduction. A modular and scalable implementation was then described and results presented from a steel test-piece, demonstrating real-time FRD imaging.

This toolbox of hardware and software modules can be used as building blocks to create a wide range of systems – whether conventional beamforming or FMC+TFM – and so support the transfer of the latter techniques for field evaluation. The paper finishes with some examples of new inspection possibilities now made possible by the use of these alternative imaging techniques.

**References**