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A modular FPGA-based ultrasonic array system for applications including non-destructive testing

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This paper reports work aimed at the development of an ultrasonic imaging system comprising modular, reprogrammable building blocks, or 'tiles', which can be customised for multiple applications, including and within non-destructive testing (NDT), by the user. The key component is an autonomous module containing the ultrasonic array and all the electronics necessary to operate it. This contrasts with most previous research on system integration which has focused only on the transducer and front-end electronics.

In the present work, a 4 × 4 element 2D piezoelectric array with a 16 mm × 16 mm aperture has been produced, with the entire transmission and reception electronics within the same footprint. The proximity of the transducer array and electronics removes the need for cabling, reducing signal degradation due to cross talk and interference. In addition, it avoids the problem of electrical impedance matching of cable between the array elements and the electronics.

Pulse-echo insertion loss of 48 dB has been measured from back-wall reflections in 73 mm-thick aluminium without decoding, and results with decoded signals show adequate signal-to-noise ratio (SNR) with ±3.3 V excitation at an operating frequency of 1.2 MHz, within the range required for deep penetration in nuclear power plant.

Crucially, the ability to construct 2D arrays of any size and shape from generic building blocks represents a departure from almost all previous work in ultrasound, which has traditionally been highly application specific. This may allow ultrasonic NDT to be used in applications for which the investment in customised devices could not previously be justified.

1. Introduction

Ultrasound systems traditionally increase sample area or resolution by increasing the number of elements(1), with a corresponding increase in the physical and electrical complexity of such systems. By adopting a different approach of using generic building blocks of 2D elements, coupled to associated electronics, a full 3D volume can be sampled from a single point allowing fast and accurate image collection with greater sample area or enhanced resolution obtainable by increasing the number of modules in use.

Due to dimensional constraints it is increasingly common for portable hand-held array-based NDT systems to have electronics in close proximity to the transducer array. Impedance matching between transducers and electronics can be hard to achieve and retain in a practical system. Cumulative impedance mismatches over time between the electronics and the individual transducers can greatly impair the signal-to-noise ratio. One possible solution lies with the avoidance of cables. Previous solutions aimed at integrating the transducer and associated electronics, usually on the same silicon substrate, have resulted in very closely coupled designs which can limit the flexibility should it be desirable to modify the array configuration to suit a particular application.

This paper presents, as an alternative, the concept of a modular ultrasonic imaging system utilising generic building blocks of 2D array element configurations to construct low-cost ultrasonic array systems of any size and shape, resulting in a fully scalable solution without requiring redesign. This system can be seen as a mosaic consisting of multiple tiles which can be tessellated to form reconfigurable arrays of any size and shape.

Each module, or tile, integrates a 16-element piezocomposite transducer array in a 4 × 4 matrix together with the analogue electronics necessary for full transmit-receive capability on all 16 channels, thus resolving the scaling difficulties that exist due to corresponding increases in quantity and complexity of transmission and reception electronics(1, 2). Unlike traditional ultrasonic systems, the drive electronics are situated adjacent to the sensor head to eliminate the use of long cables and hence minimise parasitic capacitances that degrade the strength of the received signal(1) which is of prime importance to enable low-voltage excitation.

The ability to form ultrasound systems in this way, from generic building blocks which are physically identical for manufacturing purposes yet functionally unique via programming to suit the application, has the potential to transform ultrasonic NDT with arrays as it would permit the functionality of off-the-shelf hardware to be tailored to suit any given target application(3) in a field where equipment has traditionally been highly application-specific, a point increasingly considered in research in ultrasonics(4).

The next section provides more information on the basic concept and its potential applications. This is followed by more detailed technical information and results of early tests, and finally future work is outlined.

2. The tile concept

The motivation behind this work was to miniaturise and integrate an ultrasonic system utilising a 2D piezoelectric array transducer and its associated electronics. Tessellating such tiles side-by-side would permit the construction of larger array networks, allowing control of the total aperture of the array and optimising performance for the application under consideration. Changes in the operational requirements of the system can be catered for by altering the functionality of the tiles in the system. This is the principal foundation of the MOSAIC concept presented in this paper, as shown in Figure 1 in which a single tile with electronics situated behind it can be cascaded with other tiles to form a larger array. Such a system is intended to provide the user with more flexibility in the range of applications without system redesign.

In order to be fully scalable, each building block in the system must be sufficiently autonomous so that a network comprising, for

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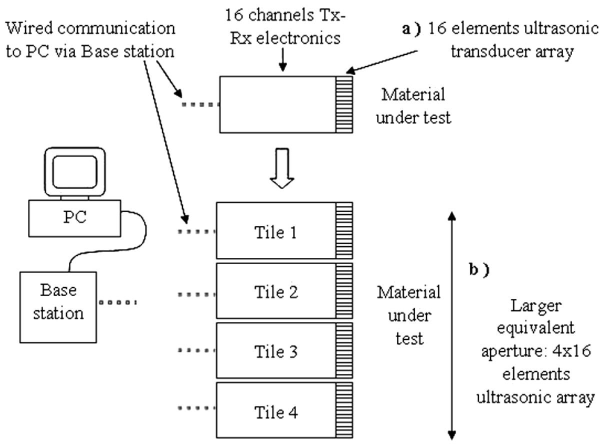

Figure 1. MOSAIC concept. a) A tile comprising a 16-element ultrasonic transducer array and integrated electronics for 16 Tx-Rx channels, b) A 64-element equivalent array aperture achieved by positioning four tiles side by side, and communicating data to a base station for processing

example 100 tiles must be as achievable as a network comprising a single tile. This necessitates the sharing of functions between tiles to be minimised.

In previous research regarding the integration of piezoelectric transducers and electronics, only the front-end analogue electronics was integrated[5]. Multiplexing the signals for each channel into analogue to digital converter (ADC) inputs is possible for a limited number of channels but does not scale well as the number of channels increase. This requires a scalable solution to a tile's electronics to incorporate the same number of transmit and receive channels as the total number of elements in the entire MOSAIC system.

Integration of CMUTs and electronics has resulted in the direct integration of MEMS and electronics by mounting an ultrasonic array onto the electronics substrate. The area occupied by the electronics is much larger than that of the array, limiting the area under ultrasonic test to that of the array size and preventing array networks being formed by adjacent tiles due to the 'dead space' occupied by the electronics[6]. In order to achieve a mosaic network capable of 3D beam steering from adjacent modular tiles, it is necessary to situate the transducer elements on adjacent tiles at the same pitch as transducers in the same module to minimise grating lobes[7]. The solution adopted was to situate the electronics behind the transducer.

Finally, it must be realised that this modular approach of electronics blocks and standardised yet flexible sub-arrays has significant potential for mass production and simplification of the fabrication processes, potentially simultaneously driving down cost while allowing end-users to access optimum performance for their applications.

3. Tile design and realisation

The MOSAIC concept lends itself to scalable solutions as a tile can be used individually or as part of a larger system, performing effectively individually or collectively. This requires the individual tile to be as flexible as possible to allow it to be configured to suit the intended application. This includes the ability to transmit and receive on any or all transducer elements using excitation sequences of any type of code or length, subject to the limitation of uniform amplitude excitation. Such flexibility is achieved by incorporating the digital electronics within the tile in a field programmable gate array (FPGA). The supplier or end-user can then program the tile as desired and two physically identical tiles can have very different functions.

The implementation of flexible electronic beam steering requires all elements in a tile to be capable of emitting and detecting signals at a 10 ns timing resolution with transmission controlled by the FPGA, as shown in Figure 2. The FPGA outputs excitation waveforms to MOSFET drive circuits to generate bipolar signals for exciting the transducer.

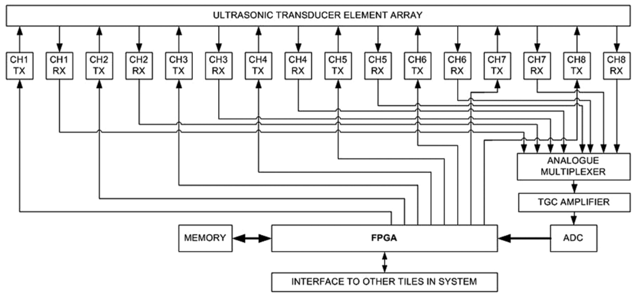

Figure 2. MOSAIC Midtile functional block diagram showing the components required for 8 Tx-Rx channels

The direct coupling of transducer and electronics provides the ability to lower excitation voltages. However, this inherently implies low signal-to-noise ratio (SNR). The flexibility to stimulate the transducer with coded excitation waveforms[8] of any length is achieved via FPGA utilisation, providing an attractive way to increase SNR. The transmission and reception electronics meet at the transducer with the lack of cables between them permitting excitation voltages as low as ±3.3V to be used to obtain adequate short-range reception signals. Each element has its own adjustable gain preamplifier after which the signals are multiplexed and time gain control is applied. A differential preamplifier prepares the signals for digitisation using a 12 bit ADC.

The FPGA formats received data for transmission to a host PC, its presence effectively decentralising a multi-tile system which is important in order to make the system scalable. Suppliers or users can implement their own front-end digital post-processing functions on the FPGA. This suits functions like filtering and averaging as these can be pipelined effectively and suit the data flow architecture, making best use of available resources without producing a data bottleneck.

As each tile in the MOSAIC system requires the same electronics, whether the system comprises a single tile or multiple tiles, the solution can be said to be truly scalable. This potentially improves upon current ultrasonic systems as it permits a generic tile to be used in a large multiplicity of applications, with reprogramming of the FPGA being the only adjustment required. Hence, it demonstrates that a cost-effective, generic solution is possible in an area traditionally dominated by application specific solutions. A photograph of a tile is shown in Figure 3.

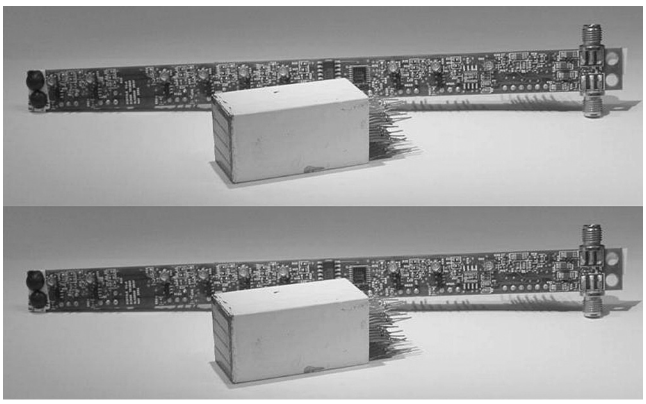

Figure 3. MOSAIC prototype tile. A 16-element prototype ultrasonic transducer array and one of two strips of Midtile electronics for 8 Tx-Rx channels. Two of these would be used to provide all the electronics for the array

4. Results

To obtain preliminary results, the transducer array shown in the foreground of Figure 3 was connected with the prototype electronics shown behind it to perform a back-wall echo test. The echo is then sensed by the same transducer in receive mode, as shown in Figure 4, which displays the back-wall echo reflection as viewed on an oscilloscope resulting from ±3.3 V excitation in an approximately 73 mm of mild steel using a 1.2 MHz transducer. The signal-to-noise ratio of the waveform is approximately 2.5 to 1.

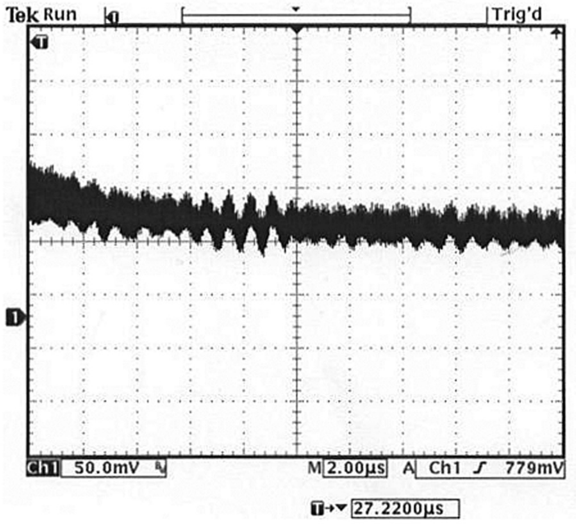

Figure 4. Reflected signal at transducer output from ±3.3 V excitation at 1.2 MHz in approx. 73 mm mild steel

To illustrate the capability of the electronics to generate an arbitrary electrical pulse excitation scheme, the transducer was excited with a 13-bit Barker code (the coded sequence used was 1,-1, 1,-1, 1,-1, 1,-1, 1,-1, -1,1, -1,1, 1,-1, 1,-1, -1,1, 1,-1, -1,1, 1,-1) with each positive and negative pulse lasting for time duration of 410 ns, corresponding to half a cycle at 1.2 MHz, and amplitude ±3.3 V. Figure 5 shows the coded back-wall echo observed after filtering to remove high-frequency noise, but before any correlation and post processing. The signal in Figure 5 was derived following application of a band pass filter of pass band 0.5 to 5 MHz to remove noise to have an approximate peak-to-peak voltage of V_{pp} = 48 mV, or -42.7 dB compared to the excitation signal. After band pass filtering it can be seen that the received signal is well above the noise floor.

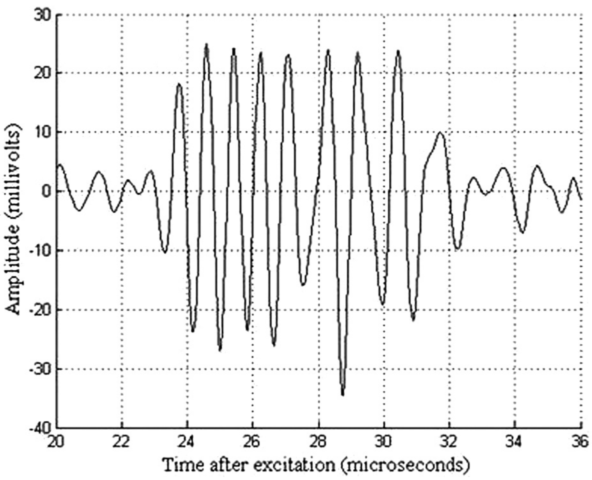

Figure 5. Filtered back-wall echo in 73 mm steel at ±3.3 V excitation

Figure 6 shows the decoded impulse response receiver data from four adjacent array elements numbered channels Rx 1 to 4 from the bottom upwards, following excitation on channel 1 (bottom most channel). The Fourier transform of the received data is multiplied by the Fourier transform of the input code and the inverse Fourier transform is taken, converting the correlated signal back into the time domain as seen in Figure 6.

It shows the impulse responses occurring close to one another but with slight lags due to the increasing distance the sound travels to transducer elements further away from the channel 1 transducer. Figure 6 shows that the impulse response of the echo is clearly distinguishable from the noise around it caused by the medium in which the sound is travelling.

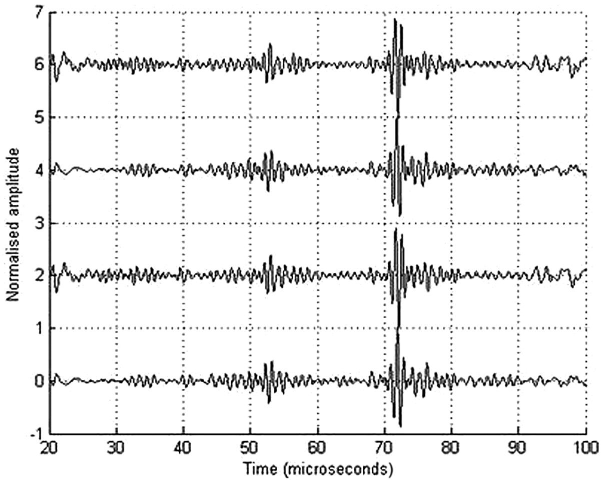

Figure 6. Correlation of received samples following excitation on channel 1 and reception on channels 1-4

Figure 7 shows the frequency response of the reflected echo in Figure 5 indicating that for the frequency range 0.5 to 5 MHz, which is the one of interest once the received signal has been applied to the bandpass filter, the normalised centre frequency is around 1.4 MHz and a dynamic range of approximately 65 dB is evident.

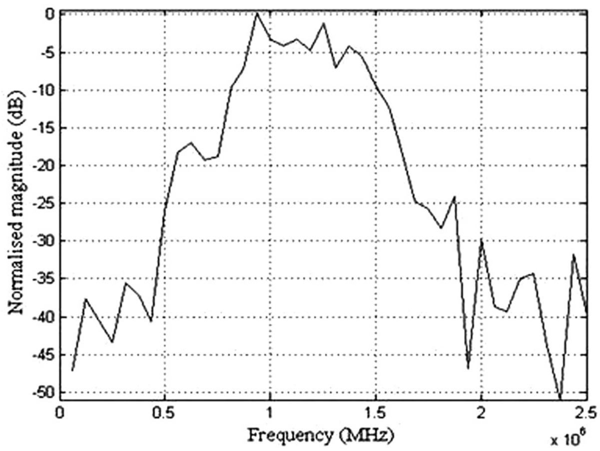

Figure 7. Frequency response of the detected echo of Figure 5

5. Conclusions

In this paper, the concept of the MOSAIC system has been introduced in the form of modular tiles designed to provide the necessary flexibility to operate in a wide range of applications without incurring substantial custom design costs. The flexibility of the system can be expressed in terms of the array configuration, the number of elements in the array, the choice of the aperture, the frequency of operation and the excitation sequence used.

The preliminary design of the electronics block has also been outlined and preliminary results of pulse-echo tests in steel have been presented. These demonstrate that sophisticated array electronics can fit within the footprint of a 16-element array and that signals with adequate SNR can be obtained, even with a tile which is not optimised for noise performance. Additional SNR gains are possible via the use of coded excitation waveforms and are easily implemented by reprogramming the FPGA.

The actual solution documented within this paper is an intermediate one and consisted of the realisation of eight transmit/receive channels on a single circuit board 12 mm wide and the FPGA housed on a separate board. 2 such analogue boards are used with a single 16 element array and a single FPGA board to create a 'Midtile'. Work has been undertaken since to integrate all the electronics for a tile on a single circuit board, housed behind the array.

Acknowledgements

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