COMPAS-XXL – A NOVEL PHASED ARRAY SYSTEM WITH EXTENDED CAPABILITIES

Gottfried SCHENK, BAM Federal Institute for Materials Research and Testing, Berlin, Germany
Roy PLOIGT, BAM Federal Institute for Materials Research and Testing, Berlin, Germany
Elmar DOHSE, BAM Federal Institute for Materials Research and Testing, Berlin, Germany
Lukas BAUER, MAZ Brandenburg, Werder, Germany
Wolfram A. Karl DEUTSCH, Karl Deutsch, Wuppertal, Germany

Abstract

In NDT with ultrasound 3-dimensional soundfield control requires a large number of instrument-channels as well as high-speed data acquisition. A matrix array of e.g. 16 x 16 elements demands 256 active receive and transmit channels, and must be equipped with a complete set of phased array specific functions as delay control, digitizers and beamforming stages. Furthermore all circuits, especially the units for conveying inspection data, have to meet strict requirements with respect to real-time-imaging. Increasing the number of channels for such arrays, although complex, has obviously huge application potential in the field of NDT. For this reason a new Phased Array inspection system, the COMPAS-XXL, has been developed at BAM in cooperation with Karl Deutsch Prüf- und Messgerätebau. The system is designed for maximum user flexibility and is based on small scalable units which may be extended up to 1024 channels.

Representing the latest member of the COMPAS (Compact-Phased-Array-System)®-family the COMPAS-XXL stands for state-of-the-art technology. Up-to-date FPGA-chips as well as brand new power-saving high-speed AD-converters were employed. As in many applications high-speed imaging is a necessity, the conversion of the raw-data of complete A-scans is performed by a special DMA-based technique. This ensures the reconstruction of inspection data in real-time. Beyond that new designed hardware techniques permit the implementation of exceptional functions as Sample Phased Array technique and simultaneous scans.

The outline extensions of the unit, another important goal, were minimized by the use of high integrated programmable technique (FPGA) and the increased application of surface mount devices. Thus a single-board unit with an on-board computer is available, which may be equipped with at least 64 channels. A special interface technique provides the assembly of 16 of these units to a complete inspection system of 1024 channels, which should be sufficient for a large variety of applications in the field of ultrasonic testing, promoting the increased employment of matrix arrays.

1. Introduction

Since Gordon Moore predicted the annual doubling of transistors integrated on a chip in 1965, well-known as “Moore’s Law” [1], chip-structures have become so small, that it is even feasible to implement most of the electronic components of a phased array system into a single chip. Therefore concepts to transfer a relevant number of stages into the probe are already on the way in medicine diagnostics and are due to reduce interconnects to the control instrument [2].

Unlike medicine diagnostics, designers of NDT-instruments dispose of smaller budgets. Therefore highly-sophisticated solutions are often not practicable, as single chip implementations, front-end electronics integration into the probe and the application of sigma-delta technique are based on cost-intensive ASIC-designs (application specific integrated circuits) [3]. This paper describes a novel phased array ultrasonic system, which utilizes the technique of field programmable gate arrays (FPGA). These devices combine the benefits of ASIC-technique: high integration and software-based design methods, with the feasibility of re-programmability and system-reconfiguration at much lower costs [4],[5].

2. System Architecture

1.1 Modular Hardware Concept

The basic conceptual idea is to assemble a variable system from identical units. Therefore the COMPAS–XXL consists of independent modules with on-board transmitter stages, receiver stages und and beam-forming stages. A proprietary bus system, the interbus, may tie 16 of these module units together. Digital stages, IO-stages and power supply components are assembled on the main-board, while transmitter stages, receiver stages and a clock unit are located on separated boards, mounted as mezzanines to the main-board. The overall-size of such a module unit is 233.4 mm length, 280 mm width and 50 mm height (standard 6U height, figure 1).

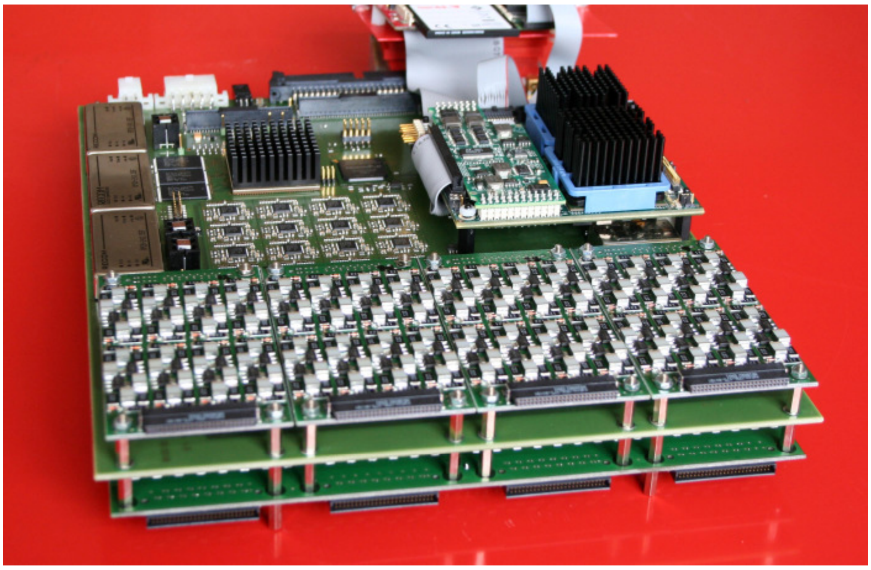

Figure 1: COMPAS-XXL module

The fully assembled system consists of a master module and 15 slave modules. The master module is distinguished from the slave modules only by being assembled with a PCI-processor board. This internal processor basically serves as an interface stage, but it may also be used for system control if a stand alone system is required. In this case mass storage is performed by the means of an on-board flash card. Figure 2 shows a system consisting of 16 modules with 1024 channels altogether.

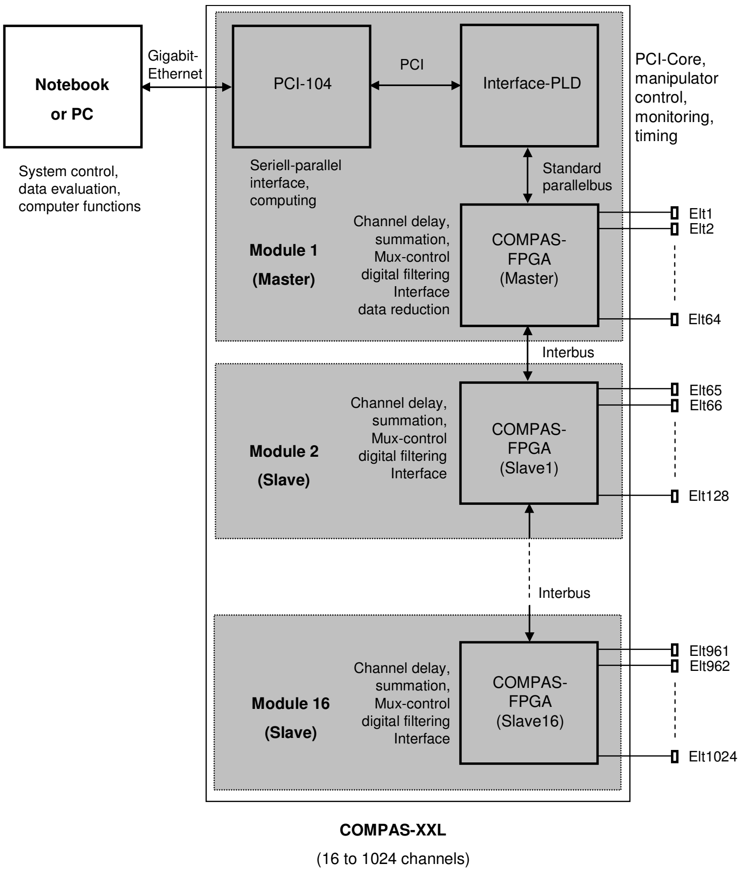

Figure 2: Architecture of the COMPAS-XXL

2.2 Main Board Unit

A highly assembled main board unit is the backbone of the COMPAS-XXL instrument. It contains the digital stages and serves as a carrier for the mezzanine boards. A very advanced FPGA-device is the heart of this main board unit. It contains all digital functions, such as interfacing, delay control, multiplexer control, data compression and an IIR-filter unit. The chip is in-circuit reprogrammable, so that system redesign may be performed easily by implementing a modified program code. The remarkable amount of 1148 connection pins serve as a gate to the environmental circuitry, for which ball grid array technique (BGA) is employed. System complexity and EMI-aspects lead to the necessity of a multilayer board with 18 layers.

2.3 Transmitter

COMPAS-XXL transmitter modules dispose of 16 channels each. 4 Modules may be mounted on a main board. The specifications are:

- Pulser type: negative rectangular
- Pulser width: 20 ns to 2500 ns
- Amplitude: 0 to 250 V
- Delay extension: 0 to 20 µs
- Delay increment: 1 ns

2.4 Receiver

Analogue amplification with programmable gain is used to adapt the level of the echo-signals of an element to the input of the ADC. Therefore COMPAS-XXL receiver module disposes of voltage controlled gain amplifier stages (VGA) with an ultralow noise preamplifier for accurate gain adjustment. The control voltage is set by a cascade of digital-to-analogue converters (DAC). COMPAS-XXL receiver modules dispose of 64 input channels, which are multiplexed to 16 amplifier channels. The specifications are:

- Amplifier type: linear
- Bandwidth: 0,4 MHz to 20 MHz (-3dB)
- Gain range: 72 dB
- Accuracy: < 1 dB
- Mux: 4 : 1
- Time-gain-control: 35 dB and 1000 increments

2.5 Digitizer

As in all digital ultrasonic equipment analogue-to-digital converters (ADC) serve as a bridge from the analogue to the digital world. The analogue echo signals received from each sensor element have to be translated into the digital code. The module-units of the COMPAS-XXL system dispose of independent ADC-stages for each channel. The specifications are:

- ADC-type: Sampling
- Sampling rate: 100 MSPS
- Quantisation: 12 bit
- Input range: 2 V_{pp}

2.6 Digital Beamformer

In receiver mode, the reflected pulses from a particular indication have to be aligned in time for each channel after analogue-to-digital conversion [6]. An advanced digital delay technique, which covers a range from 1 ns increments up to an overall delay of 20 µs, is applied in the FPGA. Internal signal-delay compensation provides perfect channel-to-channel matching. Thus programmable soundfield control, such as the variation of the angle of incidence or the adjustment of the focal point, may be performed for transducer frequencies up to 20 MHz.

The ensuing digital summation stage forms a data word of total 18 bits. Digital offset control provides correct signal levels. The specifications are:

- Digital delay extension: 0 to 20 µs
- Delay increments: 1 ns
- Offset control: 6 bit
- Summation data word: 18 bit
- Overload indication: triggered from each receiver channel
- Data format: RF-mode or full-wave-rectification
- Data compression: pixel
- Hardware gates: 4
- Interface data rate: 22 MB/s

2.7 Software

As phased array technology is utilized at BAM since the early eighties, a comprehensive bundle of programs for various functions and applications is available for the COMPAS-XXL. It implies software routines for loading the unit with control parameters and for data processing, programs for data evaluation and numerical data reconstruction, and special software tools for testing and monitoring the system during operation. Beyond such application, specific software was implemented in a number of industrial applications in which BAM phased array technology came to use.

- Operating system: Win XP
- General control software: UTinspect
- General evaluation software: UTview
- Soundfield simulation: Array Calculus
- Probe design: UTprobe
- System test: UTcheck
- Image reconstruction: A-scan, B-scan, TD-scan, C-scan, Echotomography, TOFD, SAFT

3. Operation modes

The COMPAS-XXL is suitable for a broad range of operation modes, covering conventional ultrasonic testing as well as advanced phased array techniques.

3.1 Conventional ultrasonic testing

In this operation mode the COMPAS-XXL operates as a multi-channel UT-instrument. As each channel is capable of driving a conventional probe, the user disposes of 64 channels per module-unit.

3.2 Linear Phased Arrays

The COMPAS-XXL is suitable for operating linear arrays with 256 active elements. All kind of specific probe designs like curved arrays or probes with various wedges may be adapted to the instrument. Focal laws are may be calculated by means of the BAM proprietary program Array Calculus.

3.3 Electronic scan

By switching a group of active elements (“virtual probe”) across the total of elements of a probe mechanical scanning may be replaced by time saving electronic scanning.

3.4 Matrix arrays

Matrix or 2-D arrays provide the user with the benefits of 3-dimensional scanning. As the number of elements of matrix arrays easily reach the total of several hundred ore more, the COMPAS-XXL is an ideal solution for this operation mode.

3.5 Simultaneous Scan

For applications with very high speed requirements and data evaluation in real-time, the "normal" time-sequential operation mode of Phased Array technique is not sufficient. The BAM developed Simultaneous Scan technique offers a possible solution. After transmitting into the material, echo processing is performed by a number of coincident skews, thus covering a large area of the specimen with one shot. The improved hardware-design of the COMPAS-XXL disposes of the specific routines.

4. Applications

On account of its modular structure and its feasibility for very high channel numbers the COMPAS-XXL is predestined for innovative solutions. Such as the automated inspection of round bars (figure 3), where up to 45 conventional probes may be replaced with 4 linear curved arrays [8]. Other possible applications are:

- Railway wheel-set inspection
- Turbine inspection
- Inspection of nuclear power plant components
- Weld inspection
- In-line inspection of rods and pipes
- Inspection of aircraft components
- Fast rail inspection
- Pipeline inspection

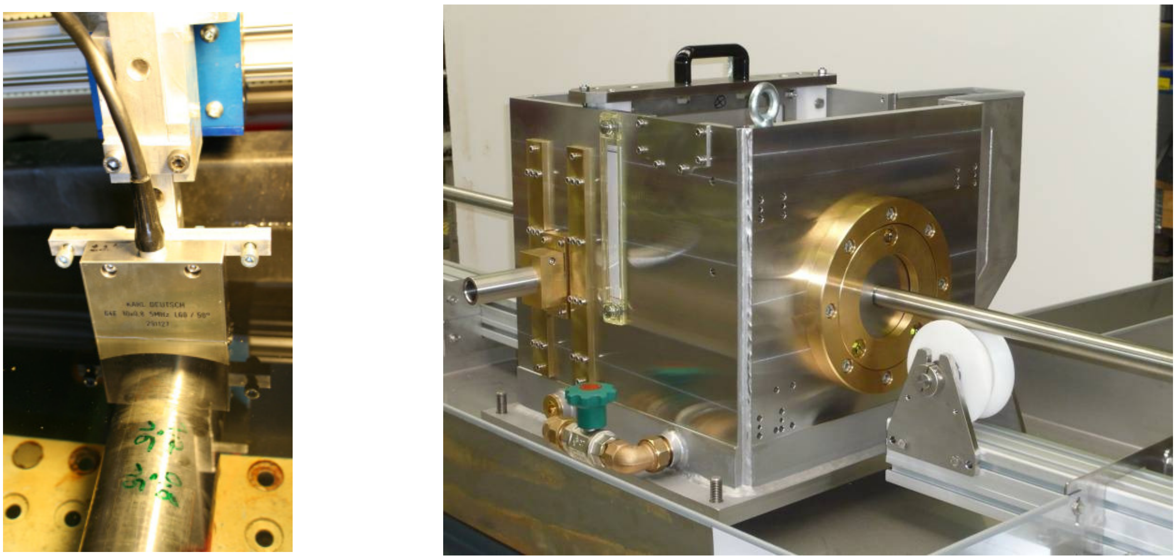

Figure 3: Round-bar testing with curved linear arrays [7] [8]

Conclusion

This paper presents a novel phased array instrument with the capability of controlling linear or 2-D arrays with channel numbers up to 1024 and high speed scanning. Its modular architecture makes it ideal for various applications, including manual inspection and automated inspection in industrial environments. In contrast to recently presented concepts, such as sampled phased array technique, the COMPAS-XXL (figure 4) is based on a full channel delay technology, which allows time-critical applications required for rail inspection and the in-line inspection of industrial products (e.g. round bars, pipes and rods) in real-time by using advanced Simultaneous Scan technique.

Figure 4: COMPAS-XXL inspection system with 128 channels

In a long tradition of instrument design at BAM the COMPAS-XXL represents the fifth generation of ultrasonic phased array system developments. As a contribution to the increasing world-wide tendency in NDT toward a broad use of this powerful technique - with its obvious opportunities: increased detection reliability, increased defect sizing, decreased inspection time, decreased number of probes and improved flexibility [9]. In comparison to its preceding model, the COMPAS-XL, a new generation of high-speed, low power components provides fast speed data transmission, an improved gate technique and the unique capabilities of Simultaneous-Scan technique.

References

[1] Vollmer, A.: „Alles Gute zum Geburtstag! Der Transistor wird 50 Jahre alt,“ Elektronik 26, 1997.
[2] Geib, H.: „Weniger Risiken und Nebenwirkungen. Cintinous-Time-Delta-Sigma-Wandler in der Medizintechnik,“ Design & Elektronik 03, 1997.
[3] Vermesan, O., et al.: High temperature phased array ultrasonic system with integrated front end electronics,” IEEE Ultrasonic Symposium, ISBN: 0-7803-9382-1, Rotterdam (2005).
[4] „ASICs auf breiter Front angreifen,“ Markt&Technik Nr.39, 2004.
[5] Weik, U.: „FPGAs in Theorie und Praxis,“ Elektronik 6, 2006.
[6] Brunner, E.: Ultrasound System Considerations and their Impact on Front-End Components,” Analog Devices, Inc., 2002.
[7] Schenk, G. et al: Prüfkonzept mit Ultraschall-Gruppenstrahlern für die automatisierte Stangenprüfung” DGZfP-Jahrestagung Münster 2009, CD-ROM.
[8] Deutsch, W.A.K. et al: „Ultrasonic Testing during Production - Semi Finished Product or Component Testing”, BANT-KINT Symposium on Nondestructive Testing, Liege/Belgium 2005
[9] Wüstenberg, H., Schenk, G.: Entwicklung und Trends bei der Anwendung von steuerbaren Schallfeldern in der ZfP mit Ultraschall,“ DGZfP-Jahrestagung Mainz 2003, CD-ROM.