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DESIGN OF INNOVATIVE MEASUREMENT SYSTEMS IN ULTRASONIC TOMOGRAPHY

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Abstract. *The article describes the progress of construction and research works on ultrasound tomography. The devices allow for non-invasive measurements of various objects using ultrasonic low and high-frequency transducers. The first constructions were made in a dispersed system with active measurement probes using 40 kHz converters. The next constructions were centralized into one measurement system where the measurement probes were connected separately. As a result, the measuring range of the supported ultrasonic transducers with 300 kHz, 400 kHz and 1 MHz has been extended. Apart from transmission and reflection tomography, the latest designs allow for controlling the ultrasound beam (beamforming) and support transducers up to 5 MHz.*

Keywords: ultrasonic imaging, ultrasonic transducers, beamforming, ultrasonic time of flight

KONSTRUKCJA INNOWACYJNYCH SYSTEMÓW POMIAROWYCH W TOMOGRAFII ULTRADŹWIĘKOWEJ

Streszczenie. *Artykuł opisuje postępy prac konstrukcyjno-badawczych nad tomografią ultradźwiękową. Wykonane urządzenia pozwalają w sposób bezinwazyjny przeprowadzać pomiary różnych obiektów z użyciem ultradźwiękowych przetworników niskich i wysokich częstotliwości. Pierwsze konstrukcje wykonano w formie systemu rozproszonego z aktywnymi sondami pomiarowymi z użyciem przetworników 40kHz, kolejne konstrukcje scentralizowano w jeden system pomiarowy gdzie sondy pomiarowe były podłączane osobno. Rozszerzony został zakres pomiarowy obsługiwanych przetworników ultradźwiękowych o częstotliwości 300 kHz, 400 kHz oraz 1 MHz. Najnowsze konstrukcje oprócz tomografii transmisyjnej i odbiciowej pozwalają na sterowanie wiązką ultradźwiękową, tzw. beamforming i obsługują przetworniki do 5 MHz.*

Słowa kluczowe: obrazowanie ultradźwiękowe, przetworniki ultradźwiękowe, formowanie wiązki, czas przelotu fali ultradźwiękowej

Introduction

There are many techniques and numerical methods for examining objects on their edge [1–4, 10–29]. Ultrasound tomography has found wide application due to the possibility of imaging in a non-invasive way in medicine, automotive industry, construction industry, chemical industry, military, etc. [5–9]. Each of these applications was preceded by research. Measuring devices designed by Research and Development Center Netrix S.A. allow researchers to develop reconstruction algorithms and study various objects using various ultrasonic transducers.

1. First version of Ultrasound Tomograph

The 1.0 and improved version 1.1 of the ultrasound tomograph performs transmission measurements using active measuring probes operating at a frequency of 40 kHz (Fig.1 and 2). The probes were connected via the CAN bus with the control unit. The measurement time of the flight data matrix in the first version of the tomograph could be saved on the SD card and sent via USB1.0.

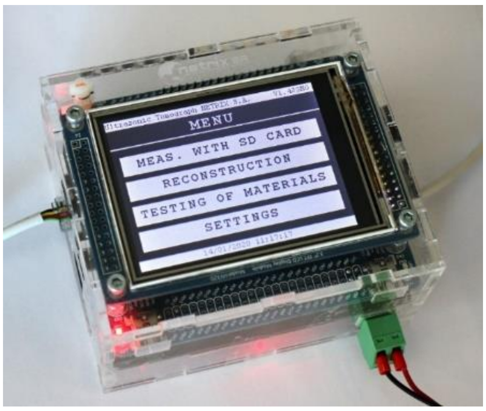

Fig. 1. Ultrasonic tomograph control unit 1.0

The next version of the control unit (1.1) allows saving data on USB flash drives and sending measurements via ETHERNET TCP/UDP and USB2.0. In the newer device, we also redesigned the user interface, and the appearance of the device housing and the speed of getting measurements were also increased.

Fig. 2. Ultrasonic tomograph control unit 1.1

The device was tested on a plastic tank, on the perimeter of which active measuring probes were mounted (Fig. 3). During the tests, the tomograph performed a series of transmission measurements calibrated in microseconds, where it measured the time of transmission of the transmitting wave from one transducer to the others and then from the next to the others until it made a full measurement matrix.

Fig. 3. Active 40 kHz probes mounted on the pipe and connected via CAN-bus

2. Second version of Ultrasound Tomograph

The second version of the ultrasound tomograph was designed to measure sound reflections using high-frequency transducers such as 1 MHz or higher (Fig. 4). The device has installed 64 multiplexed measurement channels, fast ADC 10MSPS, a square pulse generator with an excitation signal amplitude up to 144 Vp-p, a USB2.0 communication port for sending data, and a USB port to save data on the flash drive. In addition, the device performs analog measurements of the acoustic signal with the possibility of converting it to an envelope.

Fig. 4. Ultrasound tomograph 2.0

The device is made in the form of a reinforced suitcase. It makes it possible to transport the device conveniently and increases its resistance to mechanical shocks. The transmitters are connected using 8-channel industrial standard M12 sockets. In addition, the device has a touch-sensitive graphic interface for convenient operation. An additional advantage is the possibility of a remote operation via the USB port.

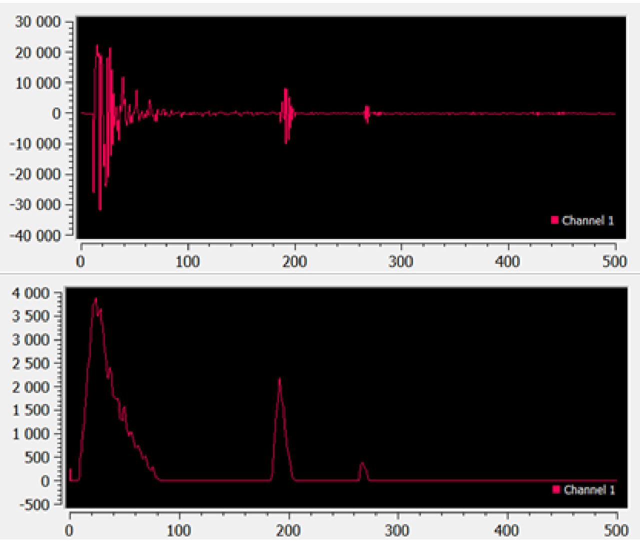

Fig. 5. Analog capture waveform via UST 2.0

The device has a defectoscope function that allows for direct imaging of the analog waveform of the reflected signal on the device screen. An analog signal or its envelope allows, using appropriate ultrasonic sensors, to investigate defects in various measurement objects (Fig. 5).

3. Third version of Ultrasound Tomograph

The third version of the ultrasound tomograph has all the advantages of the previous designs. It has 32 independent measurement channels. Each channel has its shielded measurement path, adjustable gain, three switchable analog filters for a wide range of transducers (40 kHz – 1 MHz), analog converter to the envelope with three conversion stages, 4MSPS ADC and its high voltage pulse adjustable from +/- 24V to +/- 72V (Fig. 6 and 7).

Fig. 6. Ultrasound 400 kHz transducers mounted on plexiglass tank

The tomograph can perform measurements in both transmission and reflection modes. As with previous scanners, data can be stored on USB drives or transferred via USB 2.0 to a computer. A new future in this device is the ability to send measurements to apache Kafka via ETHERNET or WiFi and the possibility of remote control from the server.

Fig. 7. Ultrasound tomograph 3.0

This enclosure, similar to the previous one, was made in the form of a reinforced suitcase, thanks to which the device can be easily transported.

The tomograph has a modern touch interface made in three languages (Fig. 8–11).

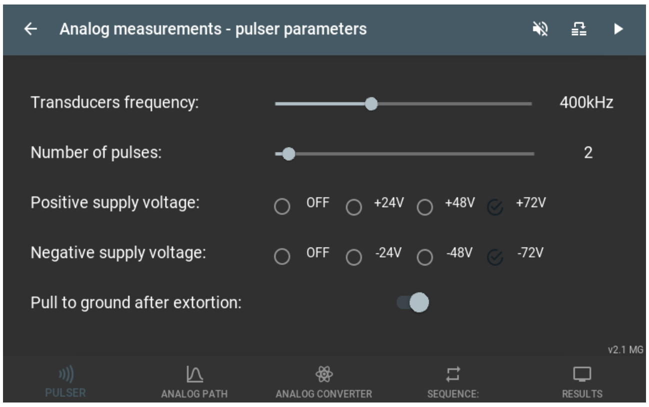

Fig. 8. UST 3.0 GUI: Pulser settings

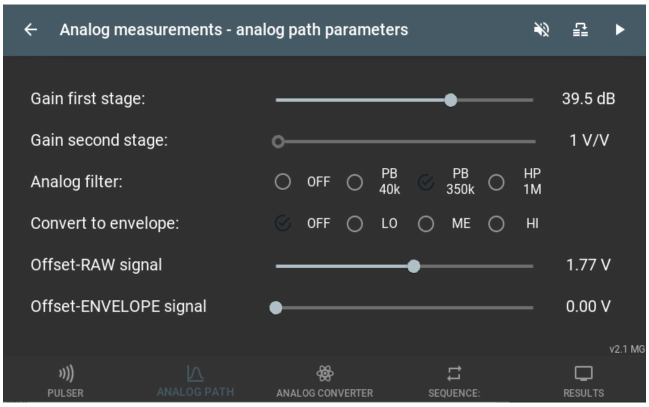

Fig. 9. UST 3.0 GUI: analog front end settings

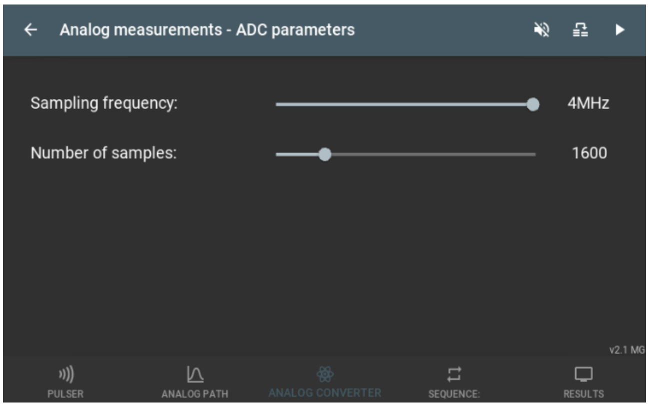

Fig. 10. UST 3.0 GUI: ADC settings

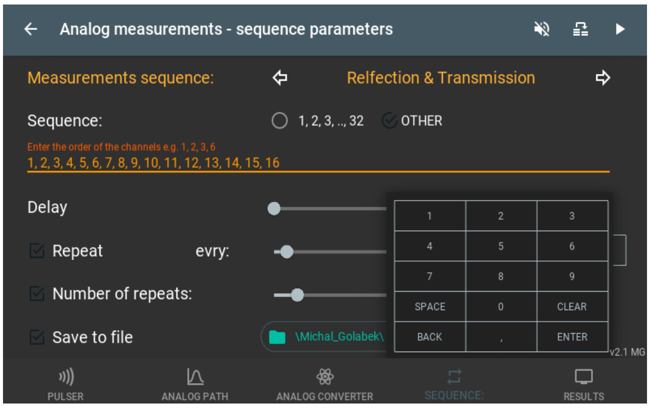

Fig. 11. UST 3.0 GUI: sequence order settings

The tomograph interface has an implemented defectoscope that allows for real-time analysis of acoustic waveforms. What can be used to detect defects in various types of materials (Fig. 12).

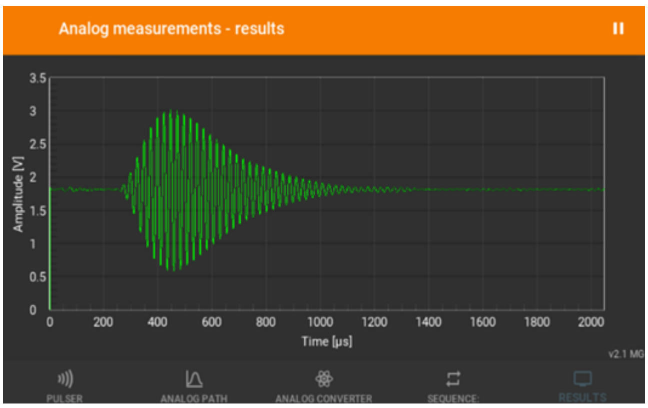

Fig. 12. UST 3.0 GUI: Captured analog signal from 40 kHz ultrasonic transducer

The system inside the reinforced suitcase consists of eight four-channel measurement cards connected via the FD CAN bus with the measurement module. The measuring module connects the microprocessor measuring system with a touch panel or an external control application. In addition, the measurement module supervises the measurement sequence, stores the parameters entered by the user, controls the high-voltage converter and switches the USB HS bus between the socket on the front panel and the touch panel (Fig. 13).

The touch panel was made using a RaspberryPi 4B 2GB RAM board and a 7-inch capacitive touch screen. The most important data buses have been led to the device's front panel.

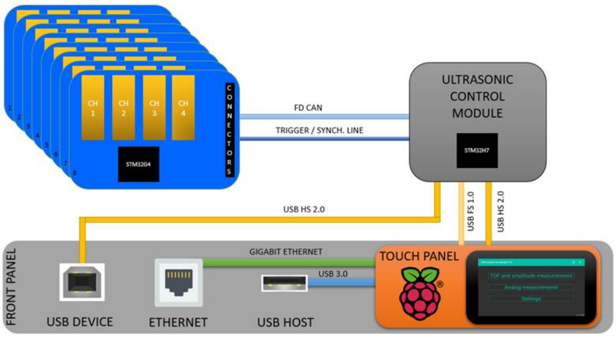

Fig. 13. Ultrasound tomograph 3.0 schematic block

Measurement card parameters (Fig. 14):

- Max sampling rate of one channel: 4 MBPS
- Each channel has a separate square wave generator with amplitude up to 144 Vp-p and current efficiency: 3 A (peak)
- A synchronous sampling of analog signal on all channels simultaneously.
- Built-in three eight-order filters on each of the channels for effective harmonic filtering, switched by analog keys:
  - A band-pass filter with 40 kHz center frequency and 50 kHz bandwidth for 40 kHz ultrasonic transducers.
  - A band-pass filter with 350 kHz center frequency and 200 kHz bandwidth for 300 kHz and 400 kHz ultrasonic transducers.
  - A high-pass filter with a 1 MHz cut-off frequency for 1 MHz ultrasonic transducers.
- Built-in envelope converter for converting an analog acoustic signal to the envelope with the possibility of switching its configuration for three frequency ranges adapted to 40 kHz, 300 kHz, 400 kHz and 1 MHz ultrasonic transducers
- Two-stage gain control on each of the channels:
  - Stage I: from + 7.5 dB to + 55.5 dB (AD8331)
  - Stage II: from + 6 dB to + 36 dB (6 presets – built-in PGA in stm32).
- Each channel is shielded, thanks to which the channels are very well isolated from each other.

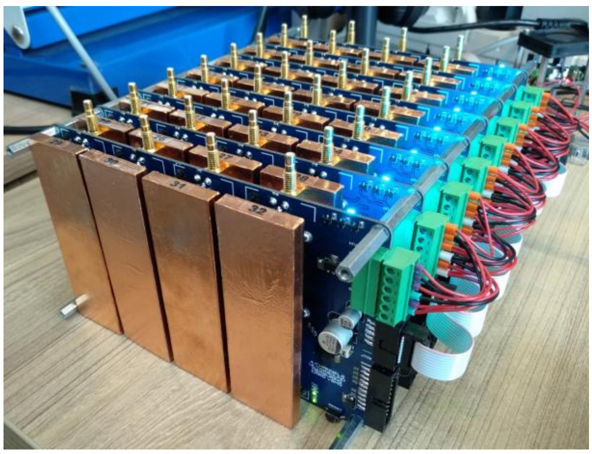

Fig. 14. Ultrasound tomograph 3.0 shielded measurements cards

4. Prototype of Ultrasound Beamforming Tomograph

Beamforming is a technology that allows focusing an ultrasonic wave beam at a specific angle or a specific point using an array of static ultrasonic transducers (Fig. 15).

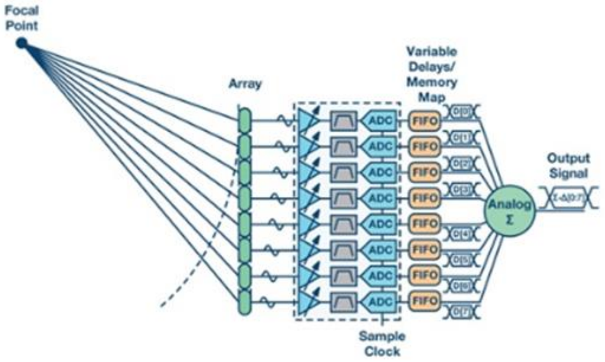

Fig. 15. Principle of ultrasound beamforming [30]

The main advantage of this technology is the ability to perform a large number of measurements using a small number of channels/transducers (and their number mainly results from the step with which the phase of the transmission signal will be shifted).

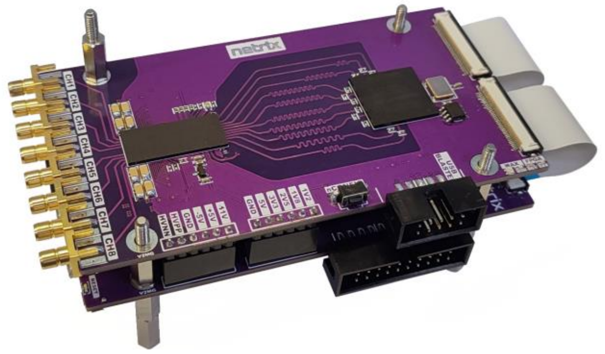

Fig. 16. Eight channels beamforming prototype board

The new prototype designed in Netrix SA opens up new possibilities in ultrasound tomography research. The construction has been reduced many times compared to the previous designs (Fig. 17).

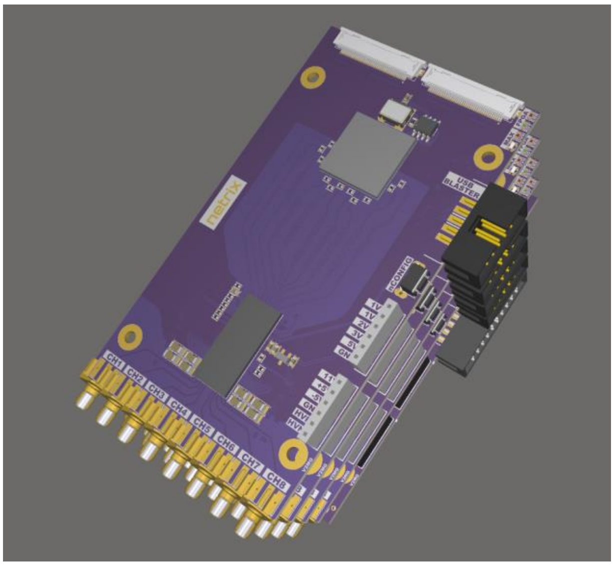

Fig. 17. 3D model of 32 channel beamforming prototype tomograph

The prototype beamforming prototype tomograph was made using the MAX2082 integrated circuit with eight independent measurement paths of ultrasonic signals. Each channel also has a 25 MSPS ADC converter with an LVDS output, a digitally controlled two high-pass filter, the ability to adjust the gain on each channel, and its 3-state +/- 72 V pulse generator. The MAX2082 chip is managed by the INTEL ALTERA CYCLONE IV FPGA chip. The collected measurement data is stored in the built-in FPGA RAM and then read via a parallel data bus by the FMC mechanism from the STM32H7 microcontroller level and then sent via USB2.0. The device has an additional USB port for control during the measurement. Delays on each of the channels can be changed using AT commands. Working multiple cards in parallel is possible thanks to the synchronization of measurement cards with a common clock, which allowed synchronizing the pulser outputs to 1 ns, with a control resolution of 5ns. The maximum speed of measurements with approximately 10,000 samples is approximately 13 ms. The device can be expanded by using additional cards up to 32 channels (Fig. 17–19).

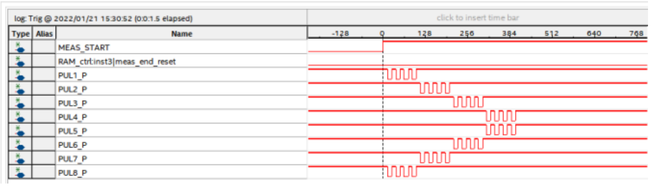

Fig. 18. Testing of beamforming eight-channel square high voltage pulser

Technical data:

- Maximum single-channel sampling rate: 25 MBPS;
- Each channel has a separate square wave generator with amplitude up to 144 Vp-p and instantaneous current efficiency: 2 A;
- The range of the transmitted ultrasonic signal: 1 MHz – 10 MHz;
- The maximum number of samples that the device can make: 16,000;
- Built-in two-row digital filter with active suppression;
- Beamforming resolution: 5 ns;
- The range of generated frequency of the excitation signal: 1 MHz – 5 MHz.

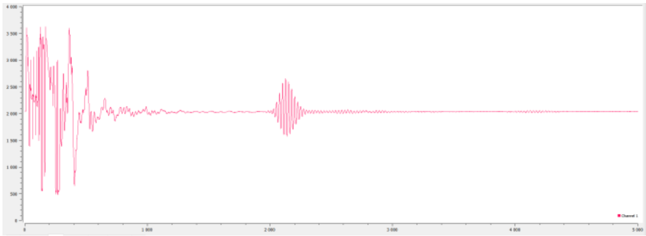

Fig. 19. Captured reflected signal from test object on 1 MHz transducer

5. Conclusion

The paper presents the author's construction of measurement devices for ultrasonic signals designed by the Research and Development Centre Netrix SA, using which it is possible to reconstruct images by solving the inverse problem. The presented solutions enable the examination of various objects using a wide range of ultrasonic transducers. Furthermore, the devices make it possible to perform non-invasive measurements of various objects using ultrasonic transducers of low and high frequencies.

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