Phased array based ultrasound scanning system development

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Abstract. Multichannel ultrasound scanning system based on phased arrays development is presented in this paper. Substantiation of system parameters is presented. The description of block diagram and hardware development is presented. The combination of the self-developed receiving and a transmitting units and commercially available FPGA unit and Personal Computer can solve our scientific goals, while providing a relatively low device cost.

1. Introduction
One of the main directions of development modern systems for ultrasound scanning, diagnostics and nondestructive testing is multichannel systems based on phased arrays.

The first ultrasound scanning systems had used one-element transducer that creates an expanding acoustic field. Ultrasound beam propagates along an acoustic axis with small expansion that allows to detect objects placed angularly relative to the beam and to measure its sizes.

The main feature of the ultrasonic phased array (PA) technology is computer controlled amplitudes and phases of the piezoelectric elements excitation pulses in multi-element transducers. Piezoelectric elements can be excited to make it possible to control ultrasonic beam parameters, e.g., radiation angle, focal distance, focal spot size by means of computer program [1]. It allows to detect arbitrary placed objects and to explore whole sections of the specimen without mechanical movements.

Our research team carries out studies in the field of development new ultrasonic phased arrays, development protective matching polymer powder coating of piezoelectric elements and echo-signal processing methods [1-7]. During our researches we face a number of problem with usage commercial PA devices. Specifically most non-destructive testing instruments are expensive and, therefore, have limited field of applications. To solve a great number of scientific and technical problems, full control of PA excitation signal parameters and full access to the received echo-signals should be provided. Existent commercial devices do not provide these features in full. Thus it is required to develop sufficiently inexpensive device for ultrasound scanning connectable with computer that meets the requirement of our researches.

2. Substantiation of system parameters
The most important parameters of PA based ultrasonic scanning system are focal distance variation range, scanning angle range, and resolutions in longitudinal and transverse directions.
Minimal measurable distance is defined by duration of the sounding pulse $\tau$, and can be estimated as:

$$d_{\text{min}} = \nu \tau,$$

where $\nu$ is sound velocity in the medium.

In this case duration $\tau$ for minimal distance $d_{\text{min}} = 1$ mm ($t = 20^0 \text{ C}$) for austenitic steel is about 0.19 $\mu$s, for human tissue is about 0.65 $\mu$s and about 0.67 $\mu$s for water.

Maximum measurement distance without taking into account attenuation in the medium is defined by the repetition time $T$ of ultrasound probing pulses and can be estimated using the following equation:

$$d_{\text{max}} = \nu T.$$

For maximum distance of 500 mm, the repetition time should be no less than 85 $\mu$s for austenitic steel and 33 $\mu$s for human tissue and water.

Axial resolution ($\delta z$) in the direction of the ultrasonic wave propagation can be estimated as [8]:

$$\delta z = \nu \Delta \tau / 2,$$

where $\Delta \tau$ is sounding pulse rise time. Modern hardware components (see for example LM96550 [9]) allow to achieve rise time $\Delta \tau < 3$ ns. While the sampling period of ADC required for this application (typical resonance frequencies of ultrasonic sensors using for nondestructive testing is about several MHz) is greater by an order of magnitude. Therefore the longitudinal resolution is defined by sampling period of ADC. For example, if sampling period is 30 ns the longitudinal resolution is $\delta d_z = 0.1 \text{ mm}$ for steel, and $\delta d_z = 0.03 \text{ mm}$ for human tissue and water.

Lateral resolution in the transverse (parallel to the active aperture of the transducer direction is estimated according to the following equation [8]:

$$\delta d_x = \frac{0.11 \nu}{f \sin(\frac{\theta}{2})},$$

where $f$ is a frequency of ultrasonic oscillation, $\theta$ is an angle of the measurement point position in relation to active aperture. Taking into account that:

$$\sin(\frac{\theta}{2}) \geq \frac{(\frac{L}{2}) \sin \gamma}{L/2 + d},$$

where $L$ is a width of the active aperture of the transducer, $d$ is a distance between center of the transducer and focal point, $\gamma$ is an angle between longitudinal axis of the phased array and a vector directed to the focal point from the center of radiating phased array. The lateral resolution for different resonance frequencies is presented in Table 1 in case when the focal point is placed on the axis being perpendicular to the array surface and passing through its center, and the transducer active aperture has width of 45 mm.
Table 1. Lateral resolution linear phased array for different medium.

| The operating frequency of the piezoelement, MHz | Lateral resolution linear phased array |   |
|-------------------------------------------------|---------------------------------------|---|
|                                                 | water, mm                             | human tissue, mm | austenitic steel, mm |
| 2                                               | 0.226                                 | 0.235            | 0.9                 |
| 2.5                                             | 0.181                                 | 0.188            | 0.72                |
| 3.5                                             | 0.129                                 | 0.134            | 0.51                |
| 5                                               | 0.090                                 | 0.094            | 0.36                |
| 10                                              | 0.045                                 | 0.047            | 0.18                |

3. Block diagram

During block diagram developing the current state of electronic components should be taken into account. At present, ultrasound scanning systems are built on large-scale integrated circuits. Each chip implements an entire multichannel hardware unit. The block diagram of ultrasound scanning system is shown in Figure 1.

![Figure 1. Block diagram of the ultrasound scanning system.](image)

The system operates under control of computer and FPGA (Field Programmable Gate Array which is one of the most efficient programmable logic integrated circuit). Communication between computer and FPGA is implemented by means of network protocol 100Base-T or USB.

The transmitting part of the block diagram consists of a transmit beamformer and transmit pulser. The transmit beamformer generates pulses with delays individually controlled for each channel to produce a probing beam turned to the required direction or focused in the required point. The transmit pulser applies 50V voltage pulses with a specified durations and delays to ultrasound transducers. The transmit pulser is controlled by the transmit beamformer signals.

The ultrasound transducer converts electromagnetic energy of the pulses into mechanical energy of the ultrasound waves. The ultrasound wave frequency is equal to the ultrasound element resonant frequency. Thus, the frequency of the ultrasound signal is determined by the probing ultrasound elements and it does not depend on the drive pulse parameters. Reflected from the inhomogeneities in the material under test ultrasound wave returns to the ultrasound transducer. The ultrasound transducer converts received ultrasound wave into electromagnetic energy.

The return signal formed by the ultrasound transducer is provided to the transmit/receive switches (T/R Switches). It should be noted that the transducer is a device which operates with both high voltage and low voltage signals, therefore T/R Switches are necessary for the high-voltage pulse protection of highly sensitive amplifying and digitizing circuits. T/R Switches work as voltage limiter.
It keeps amplitudes of probe pulses into the permissible range up to 0.5 V. The echo signals have low amplitudes and it passes through T/R Switches without restriction.

Then the echo signal is entered into the processing unit. Processing unit comprises amplifier with time variable gain (TVG amplifier), low pass filter and analog-to-digital converter (ADC). The TVG amplifier and low pass filter are required to amplify the signal up to the level ensuring high efficiency of ADC, and to filter noises and signals above Nyquist frequency. The time variable gain is required for additional amplification of the echo signals reflected from farther objects. These signals came later and they are weaker than the signal reflected from closer objects.

FPGA controls the parameters of all units (except the computer). Furthermore, the FPGA receives a data stream from a high-speed ADC, performs primary processing of the received data and transmits the data to the computer. The computer controls operation of the entire system, performs processing of the received data and displays the results.

4. Hardware components selection

Having selected hardware components the following has been taken into account:
- Compliance of chip parameters to the aimed parameter of the ultrasound device;
- Sufficient simplicity of chip mounting on printed circuit board (PCB);
- Chip availability on the local market and acceptable delivery time.

AFE5851 (Texas instruments) [10] was selected to implement TVG amplifier, low pass filter and ADC by means of one chip. The ADC outputs are serialized in LVDS (low-voltage differential signaling) streams. In Table 2 is shown its main parameters.

| Parameter                      | Value                                    |
|--------------------------------|------------------------------------------|
| Number of channels             | 16                                       |
| Variable Gain                  | -5dB to 31dB                             |
| Input Noise                    | 5.5 nV/√Hz                               |
| Low Pass Filter                | 3rd Order Anti-Aliasing Filter With Programmable Cut-Off Frequency (7.5, 10 14MHz) |
| ADC                            | Octal channel 12-bit, 65 MSPS             |

A chip TX810 [11] of Texas Instruments was selected as the T/R Switches. In Table 3 is shown its main electrical characteristics.

| Parameter                      | Value                                    |
|--------------------------------|------------------------------------------|
| Maximum Power Dissipation      | 644 mW                                   |
| Input Amplitude                | +/-90 V                                  |
| continuous wave                | +/-10 V                                  |
| Insertion loss                 | from -0.9 to -7 dB                       |
| -3dB Bandwidth                 | from 65 MHz to 140 MHz                   |
| Input Referred Noise           | 0.91 – 1.12 nV/√Hz                       |

The AFE5851 and the TX810 are dedicated to ultrasound applications using phased array transducer. They allow to implement complete receive path of the device.

The theoretical limit of the input echo-signal maximum frequency is limited by ADC and it is just over 16 MHz. The echo-signal at frequency of 9 MHz digitized by AFE5851 is shown in Figure 2.

ADC sampling frequency can be adjusted by changing frequency of the external oscillator connected to AFE5851. Therefore it has been chosen crystal controlled oscillator with frequency switch capability.
Figure 2. The echo-signal at frequency of 9 MHz digitized by AFE5851.

The AFE5851 output signal is passed to the FPGA via LVDS interface. All LVDS interface paths must have the same length. It should be taken into consideration during designing the printed circuit board.

LM96550 [9] и LM96570 [12] of National Semiconductors Corporation was selected as the Transmit Pulser and the Transmit Beamformer. The main electrical characteristics of chips is shown in Table 4.

| Parameter                          | Value   |
|------------------------------------|---------|
| Number of channels                 | 8       |
| Beamformer Delay Resolution        | 0.78 ns |
| Beamformer Delay Range             | 102.4 ns|
| Sequences                          | 64 pulses|
| 1σ Output Jitter                   | 25 ps   |
| Output Frequency Range             | 1-15 MHz|
| Output Current 2% Duty Cycle       | 2 A     |
| Output Current 100% Duty Cycle     | 0.6 A   |
| Output Voltage ±(3.3-50) V         |         |

The advantages of the used chipset are:
- They are multi-channel chips, the possibility of increasing the number of channels by increasing the chip number;
- They can be relatively easy mounted on a printed circuit board since chip terminals are located on the edge of the chip, and there are no terminals on the chips bottom;
- High reliability of the chips. The chips have successfully passed all the stages of hardware debugging.

AFE5851 and TX810 have a fairly simple power supply scheme. These chips do not require establishing the supply voltage switching sequence. This advantage is not presented to LM96550 and LM96570. They require a large number of supply voltages (7 different values), that should be applied in strong specific sequence. The special control circuit should be used to control this sequence. Therefore, if it is necessary to adjust probe pulses amplitude, one has to change two stabilized voltage simultaneously.

Four layers PCB was developed and produced for receiving and transmitting units. One of the inner layer is set for ground connections. Another inner layer is used for supply voltage connection.

While implementing FPGA unit it is convenient to use commercially available prototyping board. It has been used the Digilent Genesys™ Virtex-5 FPGA Development Board [13]. Such a board has
all required interfaces LVDS, USB, 100Base-T, and power supply stabilizers. Use of ready-made FPGA processing boards allows to save development time and resources.

4. Conclusions
Thus, it has been developed a 32-channel phased array ultrasound probing device. The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University. The combination of the self-developed receiving and a transmitting units and commercially available FPGA unit and Personal Computer can solve our scientific goals, while providing a relatively low device cost.

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