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Measurement of Ultrasound Propagation Velocity in Liquids Using an FPGA Module

Pedro Acevedo Contla (Corresponding Author)
Universidad Nacional Autónoma de México Instituto de Investigaciones en Matemáticas Aplicadas y en Sistemas Ciudad de México, México
Email: pedro.acevedo@iimas.unam.mx

D. Fabián García Nocetti
Universidad Nacional Autónoma de México Instituto de Investigaciones en Matemáticas Aplicadas y en Sistemas Ciudad de México, México

A. Joel Durán Ortega
Universidad Nacional Autónoma de México Instituto de Investigaciones en Matemáticas Aplicadas y en Sistemas Ciudad de México, México

Hugo Rolón Acevedo
Universidad Nacional Autónoma de México Posgrado, Facultad de Ingeniería Ciudad de México, México

Martín Fuentes Cruz
Universidad Nacional Autónoma de México Instituto de Investigaciones en Matemáticas Aplicadas y en Sistemas Ciudad de México, México

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Abstract

The design and development of an ultrasonic device for the measurement of ultrasonic propagation velocity in liquids based on Field Programmable Gate Array (FPGA) architecture is described. The device was implemented using a DE0-Nano-SoC Development Kit FPGA development module, a 2x16 LCD Display, a 2-channel quadrature output optical encoder with push button, two ultrasonic transducers and an external module for interfacing with the transducers containing the circuits corresponding to the transmitter, receiver and amplifier. For the development, the Altera Integrated Development Environment (IDE) software called Quartus II was used, which allows the logical design and supports different HDL hardware description languages, such as Verilog and VHLD. Although the device was calibrated to measure the acoustic velocity of water in the range of 35°C to 40°C, due to its design characteristics it is feasible to extend its application to measure acoustic velocity in different liquids, delimiting the operation intervals. The device acquires 100 readings per second, calculates the average with polynomial adjustment and displays the value of the ultrasonic propagation velocity in the fluid with a resolution of 0.01 [m/s] with a refresh rate of one second.

Keywords: Acoustic velocity measurement; FPGA array; Ultrasonic transducers.

1. Introduction

The measurement of ultrasound propagation velocity is a commonly used method for the characterization of liquids [1], since the velocity changes when certain properties are modified, such as specific heat, density, purity, state of molecular aggregation, etc.

In almost all liquids, the acoustic velocity decreases when the temperature increases, the velocity measurement is based on echo-shifts of the acoustic waves, which consists of detecting the variations of the ultrasound velocity in the medium when its temperature changes or the characteristics of the fluid change.

This work focuses on the measurement of the propagation velocity of ultrasound in water, the propagation velocity of ultrasound in water at different temperatures can be calculated using the Bilianuk and Wong equation, expressed in equation (1) [2], [3]. Where T is the temperature [°C] and c is the ultrasound propagation velocity [m/s].

$$c = 1.40238742 \times 10^{3} + 5.03821344\,T - 5.80539349 \times 10^{-2}T^{2} + 3.32000870 \times 10^{-4}T^{3} - 1.44537900 \times 10^{-6}T^{4} + 2.99402365 \times 10^{-9}T^{5} \quad (1)$$

If we consider a fixed distance between the ultrasonic transducers and a reference temperature, different times of flight corresponding to the temperature-dependent variation of the ultrasound propagation velocity in the medium are obtained [2], [3]. By comparing the flight times it is possible to obtain narrow pulses whose width is proportional to the velocity variation.

The principle of operation of the device consists of transmitting with an ultrasonic transducer a burst of ultrasonic waves that travel in the medium and are received with another ultrasonic transducer in reception; the flight time depends on the distance and the velocity of propagation of the ultrasound in the medium. The difference between flight times with respect to the time of flight of the initial velocity results in a pulsed signal that is converted to DC voltage, the width of the pulses being proportional to the change of the propagation velocity of the ultrasound in the fluid. The device allows configuring the transmission burst and the control pulses in reception, it can be easily adjusted for different operation intervals. The experimentation was performed in a water tank at controlled temperature, with the ultrasonic transducers at a fixed distance.

In Figure 1a, a container with water and two ultrasonic transducers separated at a fixed distance are shown. Figure 1b shows three signals corresponding to different temperatures, showing the difference in flight times caused by the change in velocity.

2. Materials and Methods

The DE0-Nano-SoC Development Kit FPGA Cyclone IV module from Altera's Cyclone family [4] was selected for the development of the device for measuring the propagation velocity of ultrasound in water, and the Altera Integrated Development Environment (IDE) software called Quartus II was used for the implementation, which allows the logic design and supports different HDL hardware description languages, such as Verilog and VHLD [5]. Quartus II has useful tools in logic design, which allows generating circuits at gate level code in HLD, as well as using library functions. The following items were used for development.

1. A DE0-Nano-SoC module Cyclone IV FPGA Kit [4].
2. Quartus II application software [5].
3. A support structure to fix the PVDF transducers at a fixed distance.
4. A rotary optical encoder with 2 quadrature output channels with push button [6].
5. An LCD display (2x16 LCD Display with backlight) [7].
6. A PCB external circuit.
7. Two ultrasonic transducers (Measurement Specialties, Inc, model LDT1- 028K) [8].
8. A temperature controlled water tank (Digital Thermostat Water Bath, CIVEQ, HH-2) [9].

Figure 2 shows a block diagram of the proposed device for the measurement of ultrasound propagation velocity in water, using the DE0-Nano-SoC Kit FPGA module, where it is shown that internally in the DE0-Nano FPGA module all the control signals are programmed, the acquisition of the signal through an internal analog-to-digital (A/D) converter and the display on an LCD display.

Figure 3 shows the schematic diagram of the connections of the parts that comprise the system, the DE0-Nano-SoC Kit FPGA module, the LCD display, the optical encoder, the external module, and the piezoelectric transducers.

The DE0-Nano-SoC Kit FPGA module has a programmable oscillator from which the clock signal corresponding to the operating frequency (f_o) of the ultrasonic transducer is implemented and the digital control signals shown in the timing diagram in Figure 4 are generated.

In the implementation of the system for acoustic velocity measurement, an external module is used, which contains three sections: A driver for the excitation of the PVDF transducer [8] in transmission (Figure 5a), an RF amplifier to amplify the signal coming from the PVDF transducer in reception, and a pulse-to-voltage converter (Figure 5b).

The ultrasonic signal is received by the PVDF ultrasonic transducer in reception and amplified in the amplifier circuit (RF amplifier), the amplified signal is processed in the pulse to voltage converter, which supplies a DC voltage proportional to the difference of the ultrasound propagation velocity in the liquid, the signal is acquired and digitized using the internal 12-bit A/D converter of the DE0-Nano-SoC FPGA [4].

The possibility of modifying the number of Tx burst pulses and adjusting the Rx ref pulse was considered for this application, to perform these modifications an interface was implemented to monitor and modify the Tx burst and Rx ref signals. This interface consists of a 2-channel quadrature output optical encoder with push button [6] and a 2x 16 LCD display [7]. The push button of the optical encoder is used to select the display of the following parameters: the velocity value, the number of Tx burst pulses and the Rx ref pulse delay.

In the methodology for measuring the acoustic velocity in water, a specific measurement interval is considered. First, the distance between the ultrasonic transducers is set (see Figure 2) and then using the previously described parameters; the propagation velocity is calculated using Equation (1) and the flight time of the ultrasonic wave. Considering this estimated flight time, the repetition frequency (RF) is set and the Tx gate, Rx gate and Rx ref signals are programmed (see Figure 4).

3. Results

In the design of the device, an operating frequency (f_0) of 1 MHz of the PVDF ultrasonic transducer was considered, which was generated using the 50 MHz clock of the DE0-Nano-SoC FPGA module. Taking (f_0) as a basis, all the signals of the timing diagram in Figure 4 are generated; it is worth mentioning that the delay time (*dt*) and the periods *T1* and *T2* must be programmable. The distance between transducers is set to 30 mm, the repetition frequency is 50 kHz. The Tx burst pulse is programmable from 1 to 5 pulses and the *Rx ref* pulse has a programmable delay from 20 µs to 22 µs with ±0.05 µs increments.

The 12-bit A/D converter of the DE0-Nano FPGA has a voltage reference of 3300mV; i.e. it has a quantization of 4096 *Steps* of 0.8056 mV each *digital change point*. For this application it was considered to measure the propagation velocity of ultrasound in water in a range of 35 to 40 ^{o}C. Applying Equation (1), the velocity at 40 ^{o}C is 1,519.78 m/s, and for 35 ^{o}C it is 1,528.83 m/s, so there is an increase of 9.05 m/s in the interval. Considering a resolution of 0.01 m/s, 905 A/D counts of 0.805 mV each are required, resulting in 728.5 mV at full scale.

Two experiments were performed to carry out the measurements.

Experiment 1. The water temperature in the tank (Digital Thermostat Water Bath, CIVEQ HH-2) [9] was stabilized at 40 ^{o}C , and then the ZERO adjustment was made setting the output signal of the external module to 0 mV, then when the water temperature reached 35 ^{o}C the SPAN was adjusted with an output of 728.5 mV.

Experiment 2. For the measurement of output voltages of the external module, the water temperature in the tank was stabilized at 40 ^{o}C , then it was allowed to cool slowly taking voltage readings every 0.5 ^{o}C.

Table 1 shows the voltage values obtained corresponding to the propagation velocities in the range of 35 to 40 ^{o}C, where the pulse-to-voltage converter was adjusted to provide the voltage output value at 0.0 mV corresponding to the reference temperature of 40 ^{o}C and a voltage of 728.5 mV corresponding to the full scale of 35 ^{o}C. Table 1, shows the average values of 10 readings obtained for each 0.5 ^{o}C of temperature variation in water (column B), the values of the propagation velocity calculated with Equation (1) (column C), as well as the values of the fitting curve and the values of the calculated propagation velocity.

Table-1. Average voltage values obtained for the water temperature range of 35 a 40 ^{o}C, with increments of 0.5 ^{o}C. Column B shows the measured voltages and columns H and I show the values of the ultrasound propagation velocity in the water and its corresponding error

A	B	C	D	E	F	G	H	I
Temp.	**Vmea [mV]**	**Eq. 1**	**Ideal**	**B-E**	**Curve**	**Vmea -curve**	**Display [m/s]**	**Error**
40.0	1.0	1519.78	0.0	1.0	-0.9	1.92	1519.80	-0.02
39.5	120.9	1520.76	78.9	42.0	41.2	79.68	1520.77	-0.01
39.0	217.5	1521.72	156.2	61.3	62.6	154.88	1521.70	0.02
38.5	304.5	1522.66	231.8	72.7	72.3	232.19	1522.66	0.00
38.0	382.3	1523.59	306.7	75.6	73.3	309.02	1523.62	-0.03
37.5	453.3	1524.50	379.9	73.4	67.8	385.47	1524.57	-0.07
37.0	520.7	1525.40	452.4	68.3	57.1	463.64	1525.54	-0.14
36.5	580.4	1526.28	523.2	57.2	43.0	537.43	1526.46	-0.18
36.0	635.3	1527.15	593.3	42.0	26.2	609.01	1527.35	-0.20
35.5	683.5	1528.00	661.7	21.8	8.6	674.94	1528.16	-0.16
35.0	728.5	1528.83	728.5	0.0	-10.5	738.96	1528.96	-0.13

Figure 6 shows the graph of the measured voltage values from Table 1 with respect to the temperature in the range of 35 to 40 ^{o}C (column B), and the corresponding straight line considering that the response is linear (column D). As can be seen in Figure 6, the output voltage of the external module is not linear, this nonlinearity is due to the nonlinear response of the ultrasound velocity change in the water and the nonlinear response of the pulse-to-voltage converter.

In the graph in Figure 7, it can be seen that the values in column F fit a 2nd order polynomial curve, this is because the output response is nonlinear (column B) and in the calibration two points were adjusted, the ZERO and SPAN. Since the output voltages were adjusted at the ZERO and SPAN extremes, the response of the voltage differences is a parabola, as it can be seen in the polynomial fit in Figure 7. To obtain this result the following process is performed, the voltage level provided by the external module is acquired (column B), the fitting equation *y = -0.0006x2 + 0.4246x - 1.3489* is calculated (Figure 7) and the result is subtracted from the measured voltage value (column B), obtaining the result of column E (E=B-D). As the range to be measured was set from 1519.78 to 1528.83 m/s corresponding to 40 to 35 ^{o}C, the equation *V= (Measured voltage/80.497) + 1519.78* is applied. Finally, the value of the propagation velocity is displayed on the *LCD Display* (column H).

Figure 8 shows the graphs of the values of the ultrasound propagation velocity in water, the measured values and the response after polynomial fitting.

Figure 9 shows the errors [m/s] in the measurements in the range of 35 to 40 ^{o}C.

Figure 10 shows the prototype device for measuring the ultrasound propagation velocity using a DE0-Nano-SoC FPGA module. The prototype of the device was contained in a plastic cabinet of dimensions (15 x 9.9 x 6 cm). The FPGA module and the external module have dimensions of 7.5 x 5 cm each one.

4. Conclusions

A prototype of a device was developed for the measurement of ultrasound propagation velocity in water in a range of 35 a 40 ^{o}C, using two PVDF ultrasonic transducers at a fixed distance, in transmit-receive mode and a DE0-Nano FPGA Cyclone IV module from Altera's Cyclone family and the Integrated Development Environment (IDE) software called Quartus II. A rotary optical enconder and a 2x16 LCD display were used as user interface. An external module was designed which functions as an interface with the ultrasonic transducers.

The external device module is calibrated to provide an output voltage of 0.0 mV at a velocity of 1519.78 [m/s] corresponding to the reference temperature of 40°C and an output of 728.5 mV at a velocity of 1528.83 m/s at full scale corresponding to35°C. The acquisition of the device is by means of the internal A/D of the FPGA module at 100 samples per second, averages and displays the acoustic velocity value with a resolution of 0.01 [m/s] with a refresh rate of one second.

The obtained results presented in Table 1, show that there is nonlinearity as shown in Figure 6, the adjustment is performed by applying the compensation curve in Figure 7.

The device is based on a reconfigurable architecture such as the DE0-Nano FPGA module; this allows making the *Tx burst* pulse programmable and the *Rx gate* and *Rx ref* pulses with programmable delay with increments of

±0.05 µs. By having the Rx gate and Rx ref pulses programmable, interference noise is reduced and it is possible to adjust the device for different operating intervals. This makes the system versatile for different applications. Although the device was calibrated to measure the acoustic velocity of water in the range of 35°C to 40°C, due to its design characteristics it is feasible to extend its application to measure acoustic velocity in different liquids, delimiting the operation intervals.

Acknowledgments

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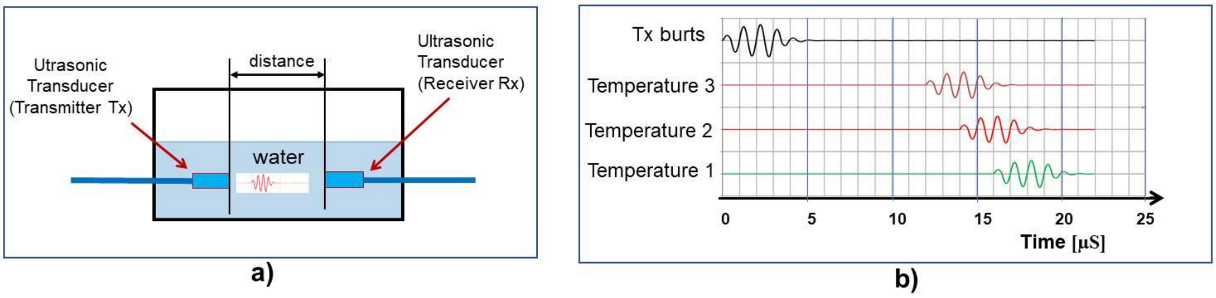
Figure-1. Principle of operation of an ultrasonic system to estimate the propagation velocity of ultrasound in water, a) experimental water tank and ultrasonic transducers, b) signals acquired at different temperatures



a)

b)

Figure-2. Block diagram of the device for ultrasound propagation velocity measurement in water, using the DE0-Nano-SoC Kit FPGA module

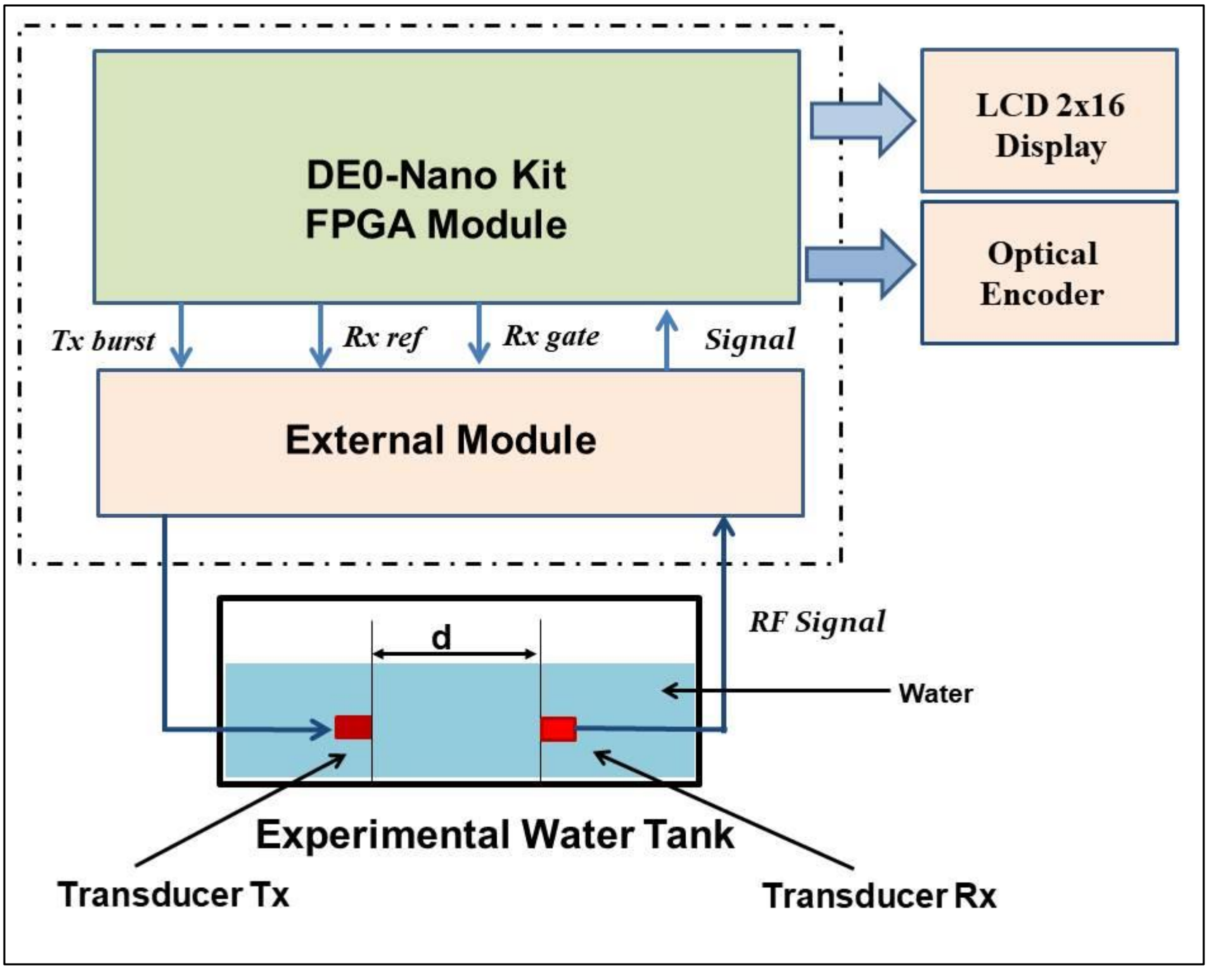


Figure-3. Schematic diagram of the device for ultrasound propagation velocity measurement in water, using the DE0-Nano-SoC Kit FPGA module

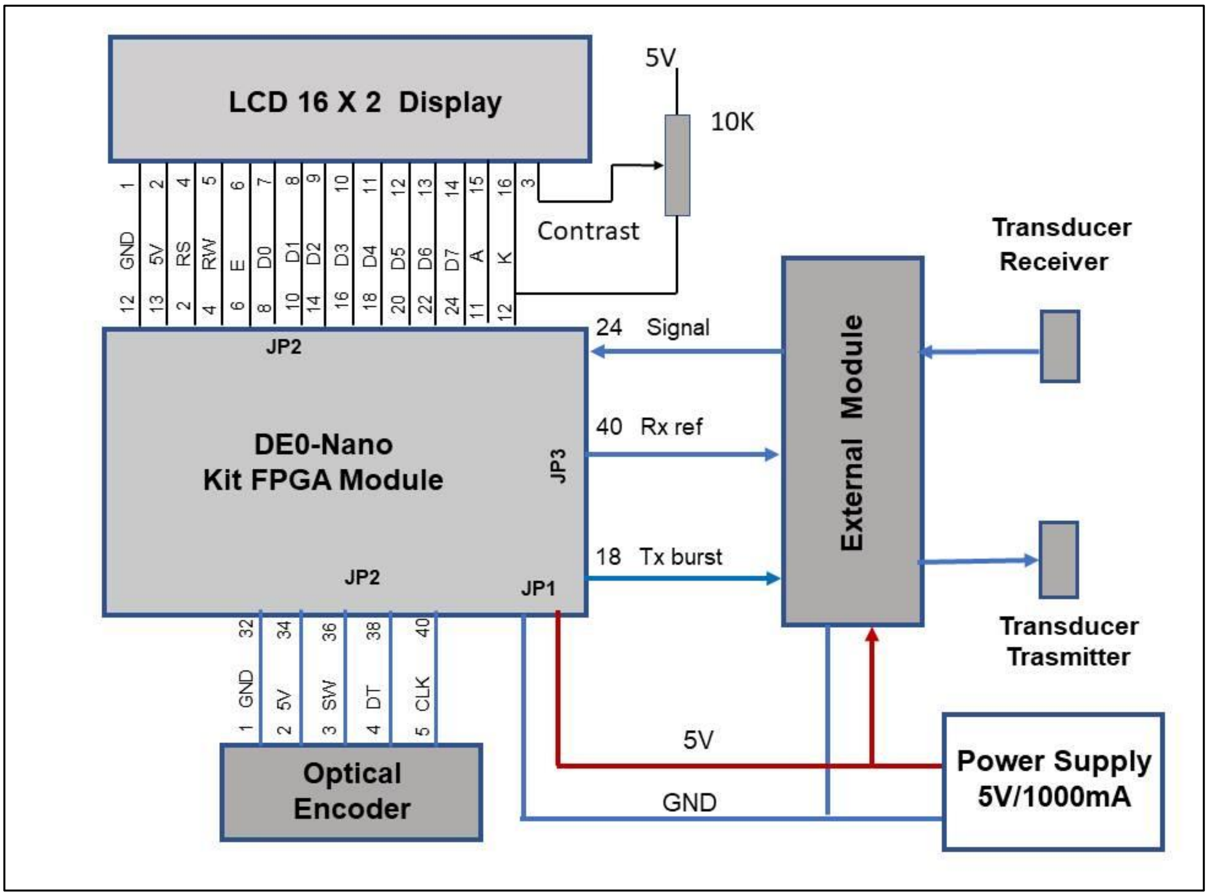


Figure-4. Time Diagram of signals required for the ultrasonic system to measure the propagation velocity of ultrasound in water

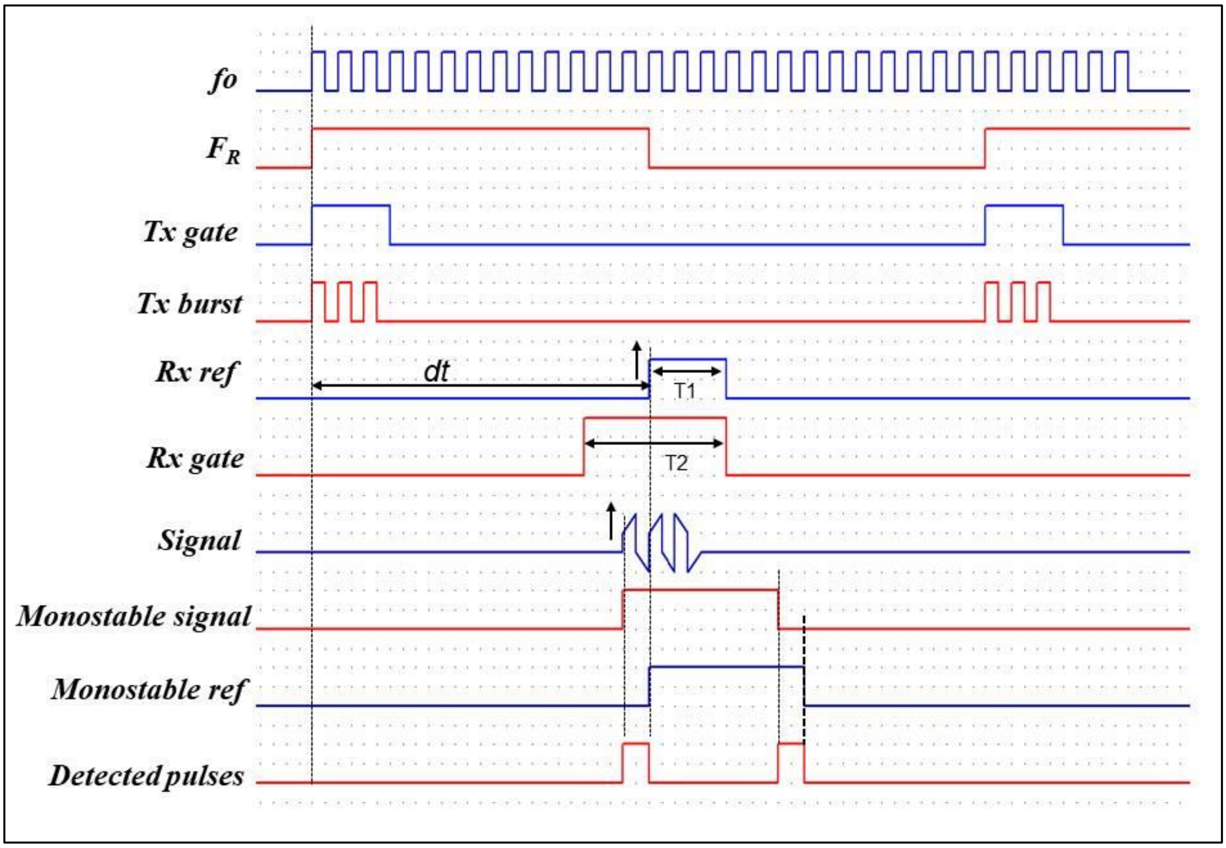
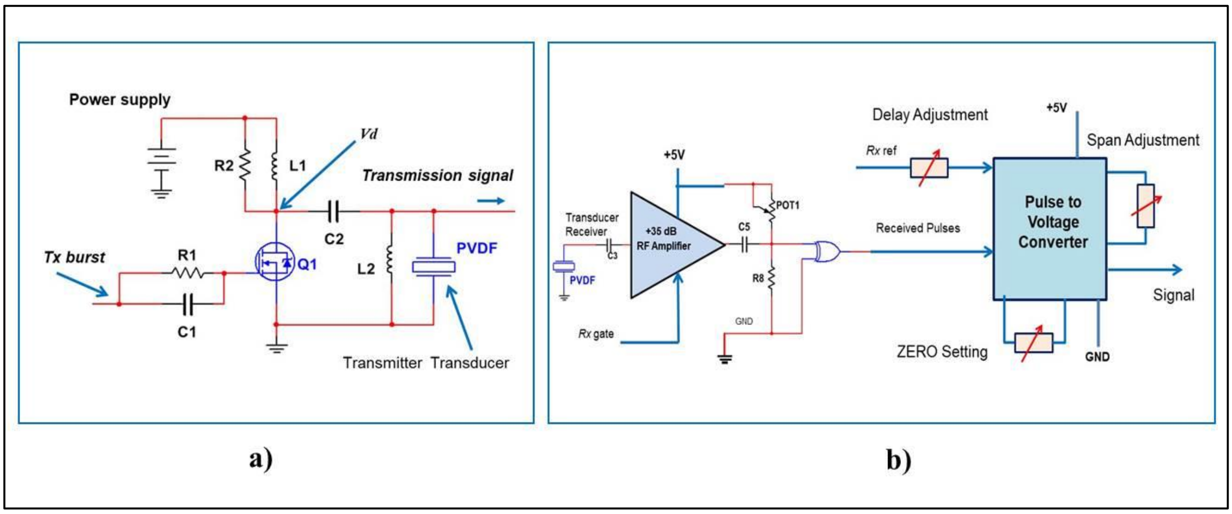


Figure-5. Schematic diagram of the external module circuits



a)

b)

Figure-6. Graph of the average voltage values (column B) of Table 1, with respect to water temperature and the line corresponding to a linear response (column D), in the range of 35 to 40 ºC

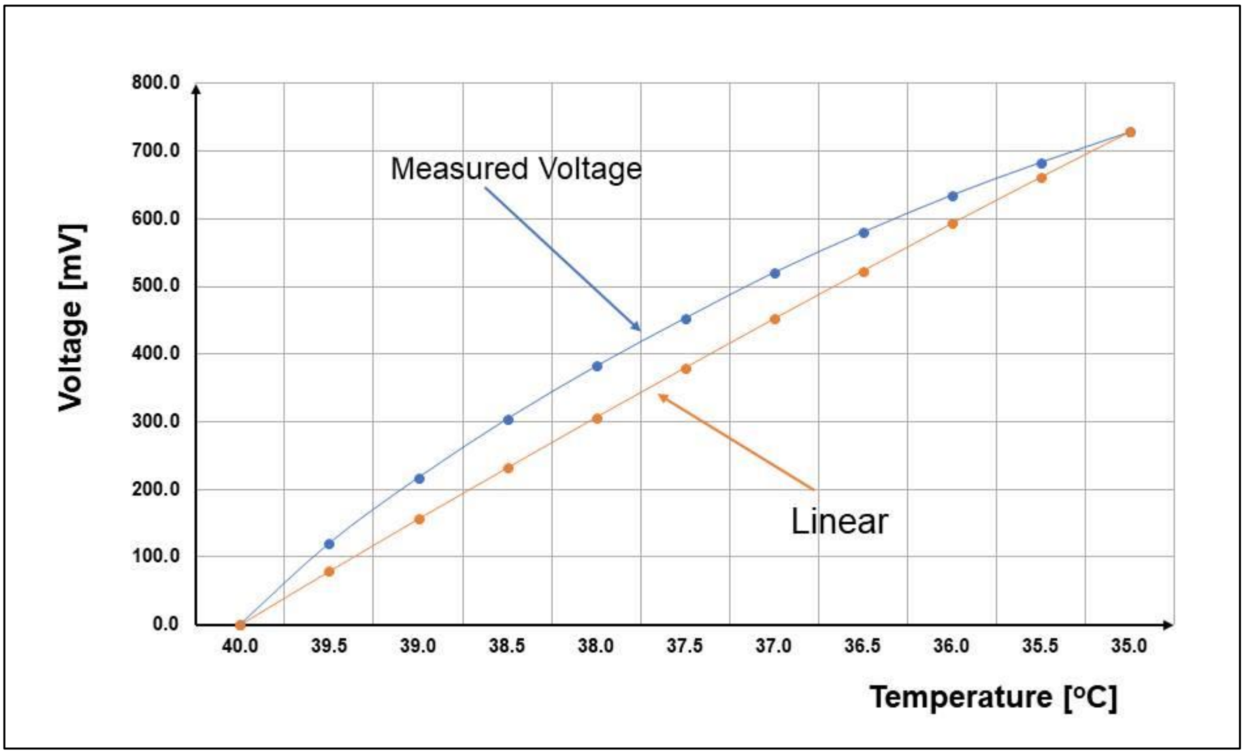


Figure-7. Graph of the values of column E, which are the differences of columns B-D of Table 1 and their polynomial approximation

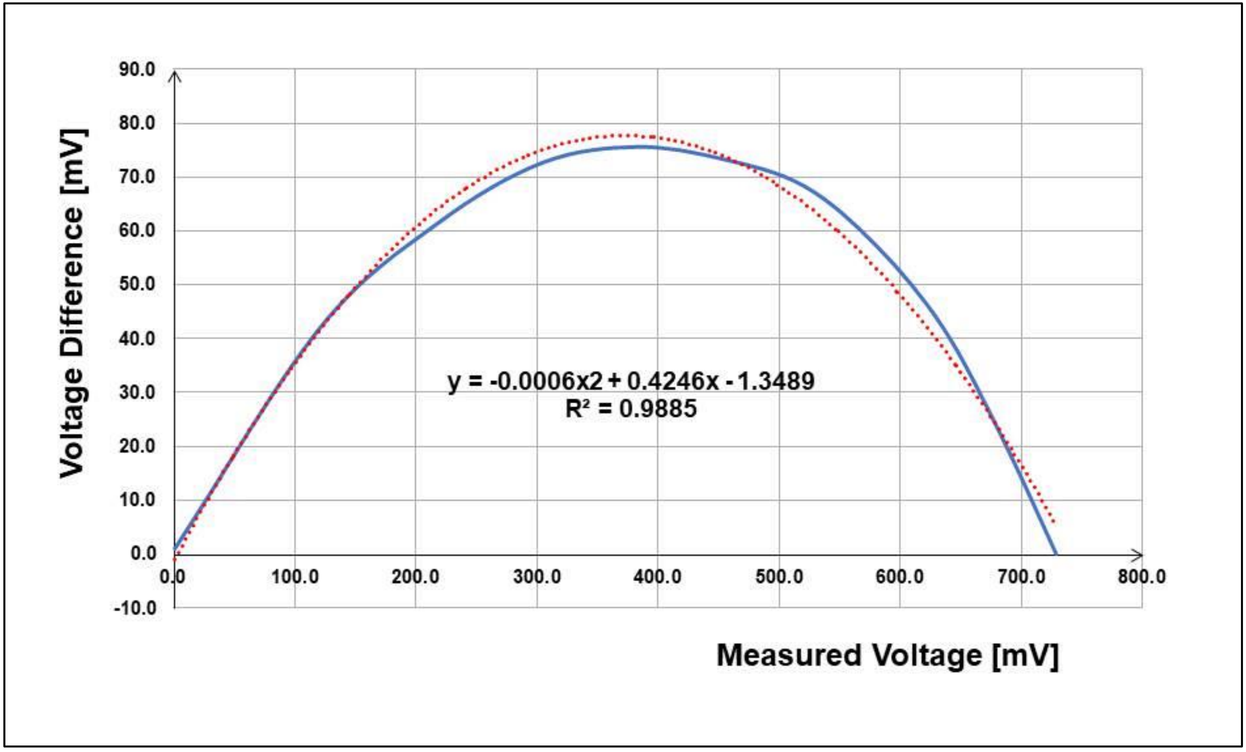


Figure-8. Graph of the values of the ultrasound propagation velocity in water, the measured voltage and the velocity value after polynomial fitting

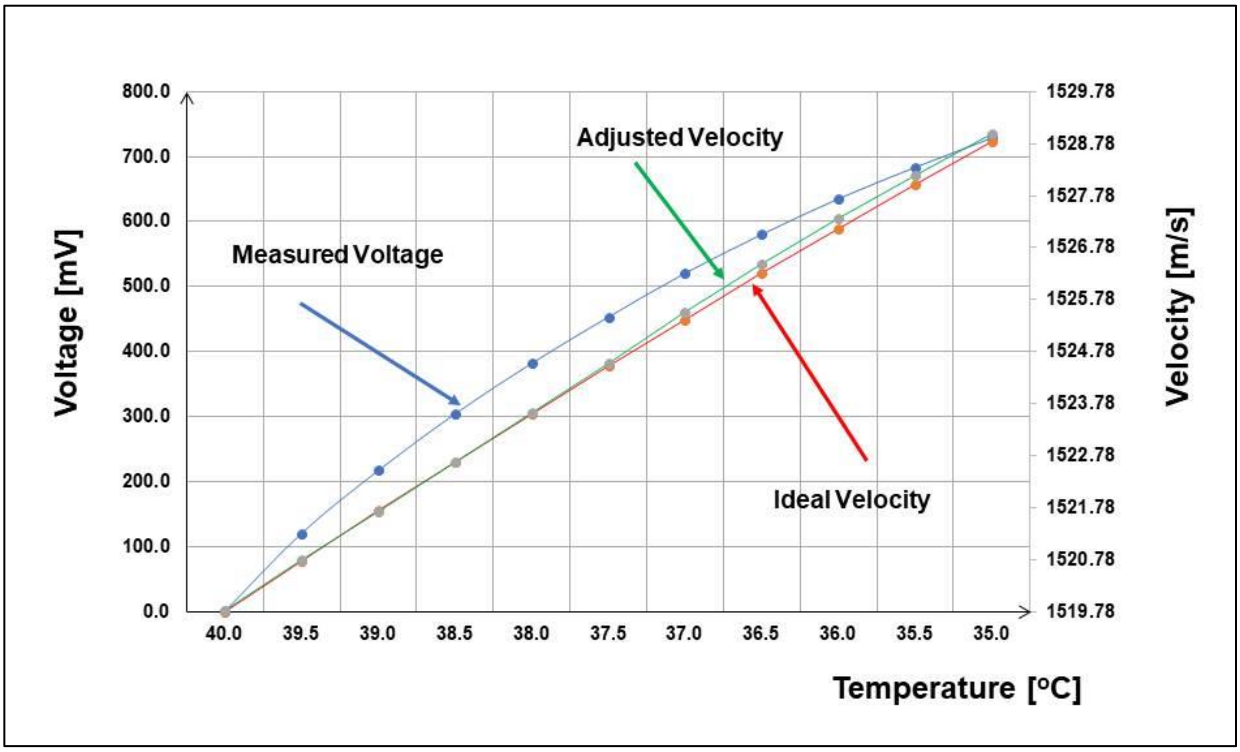


Figure-9. Graph of the error of the values of the ultrasound propagation velocity (column I of Table 1), after applying the polynomial fitting curve

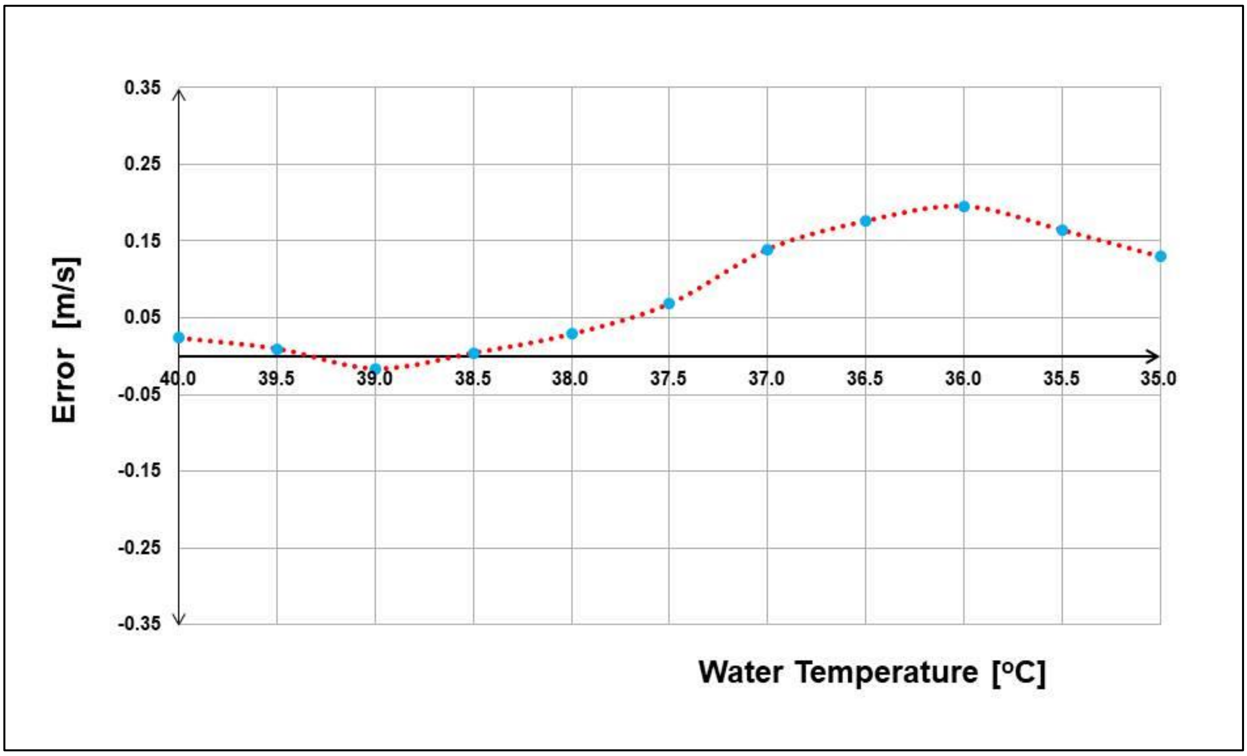


Figure-10. Prototype of the device to measure the ultrasound velocity using a DE0-Nano-SoC Kit FPGA module