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Calibration and Digital Linearization of Ultrasonic Transducer Response

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Abstract: This paper discusses the calibration and digital linearization method of ultrasonic transducer responses. The system consists of a power supply circuit, a pair of series HC-SR04 ultrasonic transducers (transmitter and receiver), a digital signal conditioning circuit using ATmega16 microcontroller and output monitor using a 16×2 LCD screen. The calibration is done by measuring the water level, and the nonlinearity of ultrasonic transducer responses has been obtained during calibration steps. For linearizing the response, we have performed the segment linearization method and finally we have obtained the fixed nonlinearity equation of transducer responses for all range measurements. The equation of nonlinearity responses is then stored in the microcontroller as a base to respond to the physics input that means the water level. Each physics input that is read by the ultrasonic transducer is further processed digitally by a microcontroller and the results are displayed on the LCD screen. The water level displayed on the LCD screen shows a linear response and is in conformity with the actual value of water level and the theoretical calculation. The average error of calibration and digital linearization compared with the theoretical calculation is 0.299 %. With the system, we can then use directly the transducer to measure and control the water level system. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Linearization methods, Ultrasonic transducer, Microcontroller.

1. Introduction

Sensor or transducer linearization response is very important performance in application, so it will provide convenience to process subsequent information. Sensor response linearization method has a variety of ways, and it all depends on the type of sensor or transducer used. The step of response linearization can be done at the analog and also at the digital step of signal conditioning circuits. Before performing calibration and linearization phase, sensors and transducers are based on a change of resistance responses, we need firstly convert the resistance change into a change of voltage or current. The various methods for the conversion as well as in the first step of analog linearization have been discussed previously. A simple and universal resistive-bridge sensors interface that is cost effective three-point measuring technique and also does not require any additional active components has been fully discussed [1].

Linearization of nonlinear nature capacitive sensors has been studied by using the polynomial linearization scheme and the improvement in accuracy is obtained by the direct linearization scheme which scales the sensor output by the nonlinear denominator [2]. Sometimes the digital linearization methods are employed in embedded system applications by using the comparison criteria of power dissipation, area, throughput, design time and rate of cost [3].

Linearization of radio-frequency sensors output has been studied by numerical method and he shows that the nonlinearity factor can be regulated by varying the capacitance of a correcting capacitor [4]. Using microcontroller as the principal linearization and calibration instrument has been shown and given the simple method in digital linearization. The equation of non linearity of sensors response can be directly stored in the microcontroller memory in order to process the nonlinearity response of sensor [5].

The lockup table of digital linearization has been minimized in order to obtain the optimal design and to reduce the memory footprint and intermediate table values are estimated by linear interpolation [6]. The dynamic measurement and correction of laser interferometer periodic nonlinearity down to the pedometer level has also been shown. They have used a capacitive sensor to be an external reference for measuring and calculating the periodic interferometer nonlinearity correction function [7].

The method of linearization of such non-linear sensors characteristics using analog electronics has been described and the theoretical explanation of the methods and its verification by experiment has also been stated [8]. Digital linearization method called ‘probability density function’ of the measured data to reduce the number of calibration points, as well as the associated calibration time, for a required level of accuracy has been shown [9]. Lastly, the analog and digital methods of linearization have been shown and the method choice depends fully on sensor type and the designer [10-12], and the 2D digital calibration of transducer response has been also studied [13].

We have also recently shown a different type of sensor linearization methods, and we conclude that the digital type of linearization method is more efficiency, small size and low cost [14–16].

In this paper, we study the calibration and digital linearization for ultrasonic transducer response and characterize the system to find the simplest digital method possible.

2. Methods

This section will explain the design of signal conditioning circuit of the system was made. The circuit is very simple because it uses a digital signal conditioner, as has been reviewed previously [5, 9-10, 13-15]. The complete circuit for linearization response of ultrasonic transducer is shown in Fig. 1.

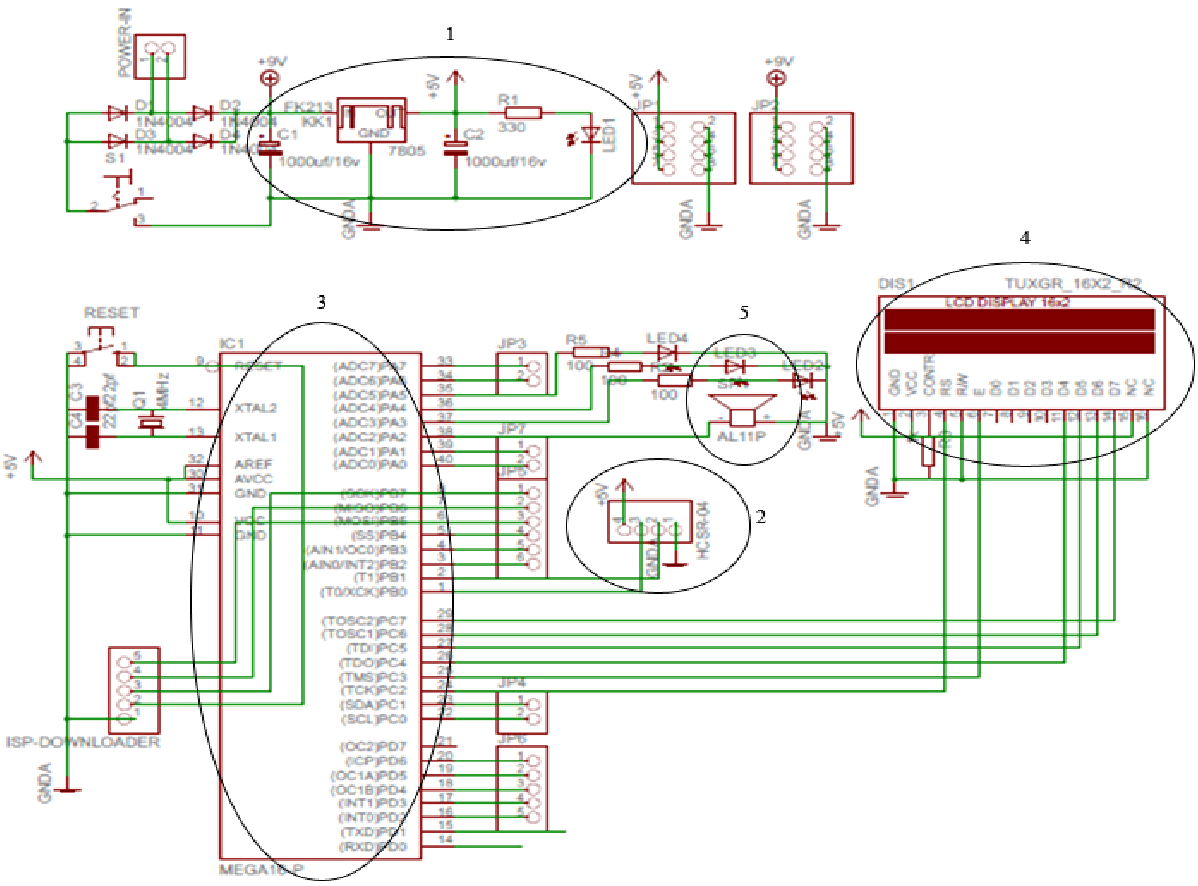

Fig. 1. The complete circuit for linearizing of ultrasonic transducer response.

The circuit consists of a DC power supply (1), a pair of series HC-SR04 ultrasonic transducers (transmitter and receiver) (2), digital signal conditioner using Atmega16 microcontroller (3), output signal will be on 16×2 LCD screen (4), and buzzer indicator (5).

The power supply of an ultrasonic transducer uses a DC voltage which is converted into a digital signal whose frequency (40 kHz) is controlled by a microcontroller through the PB0 port. The ultrasonic waves emitted by the transducer is then received by the receiving transducer and forwarded to the microcontroller through the PB1 port. The ATmega16 microcontroller has an internal ADC, so the analog input can directly be received, it's different with the AT89C51 microcontroller that we used previously [15]. The signal is then processed by a microcontroller and forwarded to the LCD screen through the PC2.7.

As we use actually this circuit to control water level of a river, we use actually the other response that means a buzzer circuit (5) which we connect it to the PA2 microcontroller port.

3. Results and Discussion

3.1. Hardware Characterization

The discussions related to electronic circuits, nothing much can be explained due to the signal conditioner used is a digital signal conditioner, the circuit is very simple. It means the linearization calibration steps are done digitally. The complete electronic circuit shown in Fig. 1, which an important remark of electronic circuit is the stability of signal response. This response stability can be achieved by verifying the grounding system and the level of electrical current from each critical point in the circuit.

As described previously, the principal of the electronic circuit for digital linearization method is microcontroller. The microcontroller controls the pulse frequency of the ultrasonic wave transmitted by ultrasonic transducer, the processing of acquisition data from the ultrasonic receiver transducer, and then finally process them into information that shown in the LCD screen.

3.2. Calibration and Digital Linearization

The simulation of data acquisition is water level in the PVC tube with a diameter of 4 inches and a length of 200 cm. The real obtained data will be compared to the measurement results (the data that appears on the LCD screen), before manipulated to be obtained the best calibration equation. Results of this first acquisition and the theoretical calculation are shown in Fig. 2.

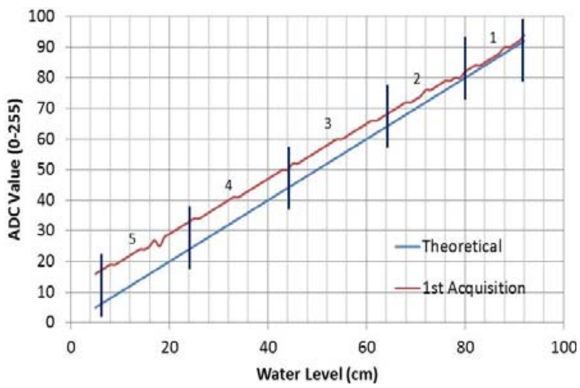

Fig. 2. ADC response for the first data acquisition and the theoretical calculation.

The original data before the data acquisition simulation are shown in red line on the graph in Fig. 2, it appears that there is a slope away from the theoretical value. The equation of the line is as follows:

$$y = 0{,}884x + 11{,}425\,, \quad (1)$$

with a correlation coefficient R^2=0,999, where y is the ADC value (0 – 255) and x is the water level (cm).

The measurement data from the first acquisition is certainly very difficult to be adapted to the actual value and theoretical calculation when using an analog system, and would require complex analog circuits. Although in fact, we can directly use the obtained equation but the problem of the error gradient must be before resolved to obtain the correct equation.

Theoretically, the data output of the ADC is actually in numeric value obtained from the water level, it can be given by the following equation:

$$N_{ADC} = \frac{V_{in}}{V_{ref}} \times 2^n\,, \quad (2)$$

where N_{ADC} is the numerical value of the ADC, V_{in} is the DC input voltage (0 – 5 V), V_{ref} is the ADC reference voltage (5 V) and n is the bit level of the ADC (8 bits).

While the input signal from the ultrasonic transducer to the microcontroller ADC port (PB0) is a DC analog voltage ranged from 0 to 5 V, so this analog voltage will be converted into a numerical value on the ADC using a DC reference voltage of 5 V. The input analog voltage V_{in} on the ADC is actually an analog voltage derived from the ultrasonic transducer output with the equation as follows:

$$V_{out} = {}^{1}\!/_{51} \times h\,, \quad (3)$$

where h is the actual water level and $^1\!/_{51}$ is the gradient with units of V/cm. The output voltage V_{out} in Equation (3) is actually the input voltage V_{in} in Equation (2).

Now let us see how we can calibrate and create a linear response in order to approach the theoretical calculation. As shown in Fig. 2, we give an indication of the cut line graphs into 5 parts. Then we make response equations for each section with only by correcting the offset control value. The offset value is the average of the different value in the entire range of the selected section. If we divide more section of the entire range of the response into several sections, the results of the calibration and linearization will be smooth and better. This step has the disadvantage that the program will be longer so it will need much memory of the microcontroller, and also the process of data conversion into information will be longer. The part of the main program that we have stored in the microcontroller is as follows:

```
h = 100 – ADC_value
h = h
'calibration step1
If h <= 100 And h > 80 Then
X = h - 1
X1 = X + 500
X1 = X1
End If
'calibration step2
If h <= 80 And h > 62 Then
X = h - 3
X1 = X + 500
X1 = X1
End If
'calibration step3
If h <= 62 And h > 42 Then
X = h - 5
X1 = X + 500
X1 = X1
End If
```

The program has been stored in the microcontroller memory, so that any numerical value that comes out from the internal ADC will be processed by the equations in the program. The report of the process will be directly displayed on the LCD screen. The results of calibration and linearization correction are shown in Fig. 3.

Fig. 3 shows the final results of the calibration and linearization of ultrasonic transducer response. We see that the error gradient on the results of the first acquisition (Fig. 2), now it is not present in the calibration graph in Fig. 3. The results of calibration and linearization have shown by the brown graph in Fig. 3, where the graph has the following equation:

$$y = 1{,}006x - 0{,}497, \tag{4}$$

with a correlation coefficient R^2=0,999.

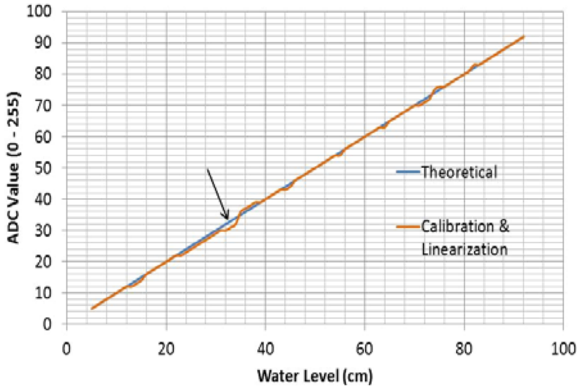

Fig. 3. The calibration and digital linearization results and the theoretical calculation.

Now, we know that the result of the manipulation of the first acquisition data (brown graph in Fig. 3) is very close to the theoretical calculation (blue graph in Fig. 3), so the graph of theoretical result is covered by the calibration graph. In theory, we have a calibration equation which is a combination of Equations (2) and (3), as follows:

$$N_{ADC} = \frac{^1\!/_{51} * h}{5} \times 2^8, \tag{5}$$

$$N_{ADC} = 1{,}003 \times h \tag{6}$$

The Equation (6) is the equation of the theoretical linear response between the water level (h) and the output value of the ADC (N_{ADC}). The results of the calibration and digital linearization that we get are shown in Equation (4) with the offset value of -0.497. In Fig. 3, it still seems there is small difference between the results of the calibration and digital linearization to the theoretical calculation, as indicated by the arrow. The error in the range indicated by arrow is about 9.091 % for water level range from 32–35 cm. In this section, we can actually add an equation for this range measurements according particularly to the arrow in order to obtain really the same value with the theory. However, this has not been done and we think not so necessary at this time because at our application, the water levels we measured are in the range of 40-90 cm.

The average error for all measurements range of calibration and digital linearization compared with the theoretical calculation is 0.299 %. This error value is also then reduced by offset value. We can see that the system we have developed has a perfect linear response. This perfect linear response means that any physical quantity coming into our system, its output response shown on the LCD screen has exactly the same value with the input (shown in Fig. 3).

Finally, we can easily give the units of the numbers on the LCD screen with the water level units, which is in cm. The calibration and linearization process give us the main conclusion that the method of digital calibration and linearization has the most convenient, high precision, simple, the process is fast, easy to be corrected again, and of course the dimensions of the circuit will be small, as noted previously [5, 13-16].

4. Conclusions

We have shown the method of calibration and digital linearization of the ultrasonic transducer response to be precise to the actual value and also the theoretical calculation. The method what we have used is in digital level, it means in stored software section and no hardware modifications to the circuit. This is what strengthens of our conclusion that the method of sensor or transducer calibration and linearization would be easier if it is done digitally.

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References

[1]. Sergey Y. Yurish, A simple and universal resistive-bridge sensors interface, *Sensors & Transducers Journal*, Vol. 10, Special Issue, February 2011, pp. 46-59.

[2]. Barun K. Kar, Eric Joseph, Linearization techniques for capacitive sensors, *Proceedings SPIE, Micromachined Devices and Components*, 2642, 15 September, 1995, pp. 206-214.

[3]. Betat O., Carro L., Comparison of digital linearization methods for embedded sensor interfaces, in *Proceedings of the IEEE International Symposium on Circuits and Systems (ISCAS'02)*, Vol. 1, 2002.

[4]. V. Ya. Fateev, Numerical study of methods of linearization of the output characteristics of radio-frequency sensors of the level of dielectric media, *Measurement Techniques*, Vol. 54, No. 7, October 2011, pp. 774-780.

[5]. Gert van der Horn, Khalid Lyahou & Johan Huijsing, Calibration and linearization method for microcontroller-based sensor systems, *Measurement & Control*, Vol. 29, November 1996, pp. 270-273.

[6]. Lars E. Bengtsson, Lookup table optimization for sensor linearization in small embedded systems, *Journal of Sensor Technology*, Vol. 2, No. 4, 2012, pp. 177-184.

[7]. Jeremias Seppä, Virpi Korpelainen, Mikko Merimaa, Gian Bartolo Picotto and Antti Lassila, A method for linearization of a laser interferometer down to the picometre level with a capacitive sensor, *Meas. Sci. Technol.*, Vol. 22, No. 9, 2011.

[8]. Dilip Kumar Ghara, Debdulal Saha & Kamalendu Sengupta, Implementation of linear trace moisture sensor by nano porous thin film moisture sensor and NLAmp, *International Journal on Smart Sensing and Intelligent System*, Vol. 1, No. 4, December 2008.

[9]. Pereira J. M. D., Postolache O., Girao P. M. B. S., PDF-based progressive polynomial calibration method for smart sensors linearization, *IEEE Transactions on Instrumentation and Measurement,* Vol. 58, Issue 9, Sept. 2009, pp. 3245 - 3252.

[10]. Lopez-Martin A. J., Carlosena A., Sensor signal linearization techniques: A comparative analysis, *IEEE Fourth Latin American Symposium on Circuits and Systems (LASCAS)*, 27 Feb. 2013-1 March 2013, pp. 1-4.

[11]. Jiri Keprt Petr Benes, Determination of uncertainty in calibration of acoustic emission sensors, in *Proceedings of the 4th International Conference on NDT*, *Hellenic Society for NDT*, Chania, Crete – Greece, 11–14 October 2007.

[12]. M. Nadi, C. Margo, M. Kouider, J. Prado, D. Kourtiche, Embedded system design and implementation of standard auto-calibrated measurement chain, *International Journal on Smart Sensing and Intelligent Systems*, Vol. 1, No. 1, March 2008, pp.21-33.

[13]. Aleksandar C. Zoric, Dragoljub Martinovic, Slobodan Obradovic, A simple 2D digital calibration routine for transducers, *Facta Universitatis (NIS), Ser.: Elec. Energ*., Vol. 19, No. 2, August 2006, pp. 197-207.

[14]. Warsito, Gurum A. Pauzi, Sri Wahyu Suciyati, K. Imaniar, Study of inclination angle of reflector object in simple water level instrument using 40 kHz ultrasonic transducer, *Journal of Theoretical and Applied Information Technology*, Vol. 42, No. 1, 2012, pp. 1-5.

[15]. Warsito, Gurum A. Pauzi, Sri Wahyu Suciyati, Turyani, Design and characterization of high resolution water level detector using MW22B multi-turn potentiometer, in *Proceedings of the American Institute of Physics Conference Proceedings,* Vol. 1454, 2011., p. 174.

[16]. Warsito, Sri Wahyu Suciyati, Novi Irawan, Low frequency measurement of mechanical vibration using optocoupler sensor and cantilever system, *Sensors & Transducers,* Vol. 172, Issue 6, June 2014, pp. 91-97.

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