An Enhanced Effective Angular Position Encoder Linearization System

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ABSTRACT: *With the help of a specific microcontroller we have presented a cost-effective angular position encoder linearization system. This model is introduced and used to increase the encoder resolution and accuracy. During the testing we found that this encoder resolution is increased by three bits, and there is an increase of ten times the maximal absolute measurement error.*

Keywords: Angular Position Determination, Linearization, Pseudo-linear Signal, Sine and Cosine Signal Processing

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1. Introduction

The angular position encoders are widely used transducers in many systems that contain rotating parts [1]. However, the non-linearity of the encoder static transfer function results in low sensitivity, meaning that even significant change in the measured angle leads to insignificant output voltage variation [1, 2]. Sometimes these output voltage variations are so small that the noise present in the signal or signal distortion can mask them. If the variation of encoder output voltage is not detected, the measured angle change will not be detected as well, producing in this manner a significant measurement error. In order to avoid this kind of error, a linearization technique can be used [3-6].

To gain more accurate information about the absolute angular position, one can use the interpolation electronics for processing of encoder output sine and cosine signals [7]. However, the interpolation method is based on information about the relative difference between sine and cosine signal amplitudes and phases, so the deviation of these signals from the ideal signal waveforms can cause an error. Therefore, it is important to eliminate these deviations before the signals are brought to the inputs of the interpolation electronics.

The aforementioned problems can be avoided using the encoder linearization system presented in this paper. The developed linearization system is reliable and by its price cost-effective solution that enables the angular position measurement resolution increase by three bits. The system is consisted of a linearization circuit (a network of logic circuits, comparators, operational amplifiers and a multiplexer) and the PIC18F2550 microcontroller (MCU). Result of the application of this system is lower absolute measurement error, while the shortcomings of complex and processor demanding digital linearization methods are avoided [8].

2. Linearization System Design, Functioning and Application Results

Angular position encoder generates highly nonlinear sine and cosine signals at its output as a response to an angular position change, [1]. By processing these signals with the proposed linearization circuit more linear resulting signal, socalled pseudo-linear signal, is obtained. Pseudo-linear signal is composed of the most linear parts of sine and cosine signal. In addition to the output pseudo-linear signal, the proposed linearization circuit generates three bits used for coding of an octant, $\pi/4$ [rad] wide, (within the range of 2π [rad]) to which the measured angle belongs. Further processing of the signal (for example A/D conversion using the A/D converter (ADC) built-in in the MCU) is carried out within one octant, so that the ADC input range is narrowed down.

The proposed linearization system is tested using a PC with the LabVIEW virtual instrument used to generate the encoder output signals that are brought to the respective inputs of the linearization circuit via PCI-6251/CB-68LP Academic Starter Kit (consisted of the PCI-6251 multi-function acquisition card and CB-68LP connecting block). In addition to the linearization circuit, the newly-designed printed circuit board contains the PIC18F2550 MCU whose built-in 10-bit ADC performs conversion of analog pseudo-linear signal of improved linearity into digital domain. The shape of the pseudo-linear signal (voltage), that is being further digitized, is the same as the shape of the sine function within the range from 0 to $\pi/4$ [rad]. The MCU forwards the 10-bit digitized voltage to the PC via built-in HID USB connection. Additional virtual instrument, installed on the PC, determines the value of the angular position using the first three bits and the output of the 10-bit ADC, and displays the result on the front panel. Testing scheme of the proposed linearization system is shown in Figure 1.

Electrical scheme of the linearization circuit used for the pseudo-linear signal generation is shown in Figure 2*a*. The sine and cosine signals are brought to the inputs of the comparators in order to be compared with the zero reference voltage, or in order to be mutually compared. By bringing digital signals A, B, C and D to the inputs of the logic circuits shown in Figure 2*a*, special logical operations are performed, while the following bits are generated:

$$D_2 = \overline{\mathrm{A}}, \tag{1}$$

$$D_1 = \mathrm{A\ XOR\ B}, \tag{2}$$

$$D_0 = (\mathrm{A\ XOR\ B})\ \mathrm{XOR}\ (\mathrm{C\ XOR\ D}). \tag{3}$$

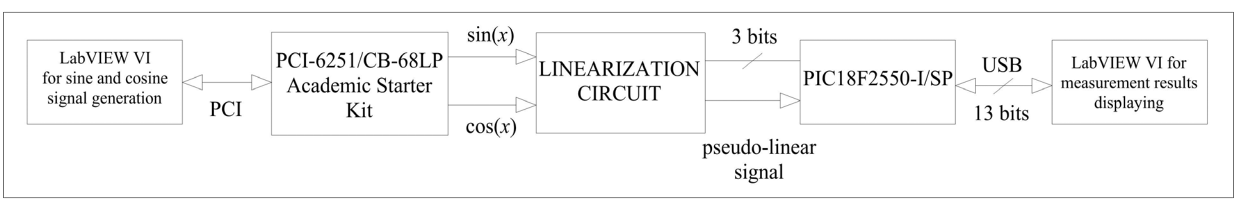
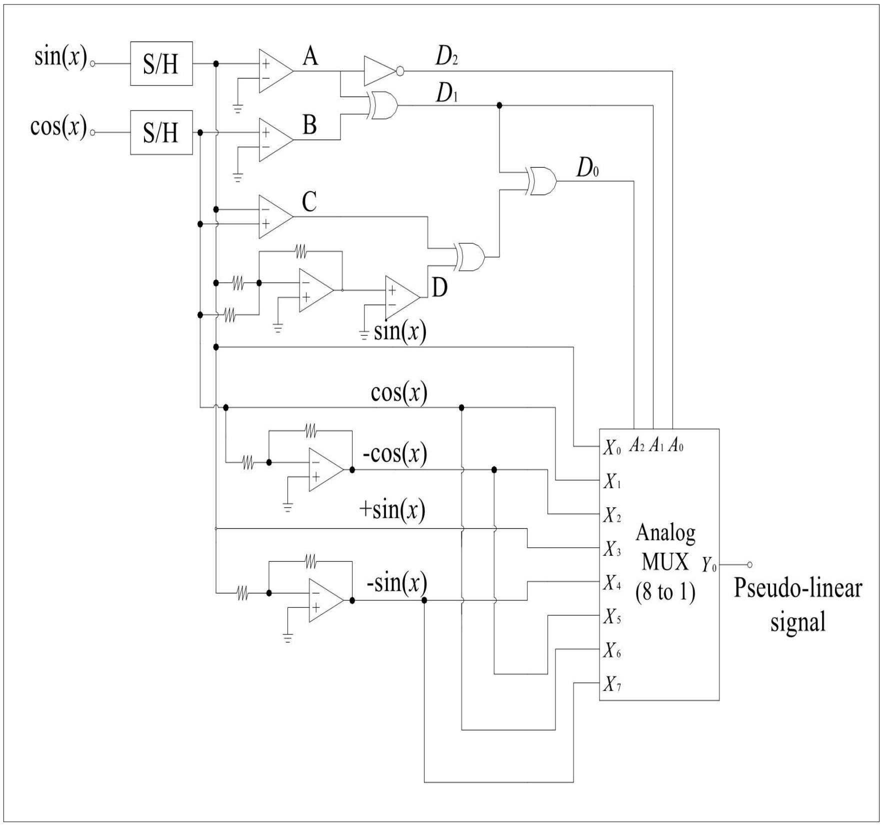


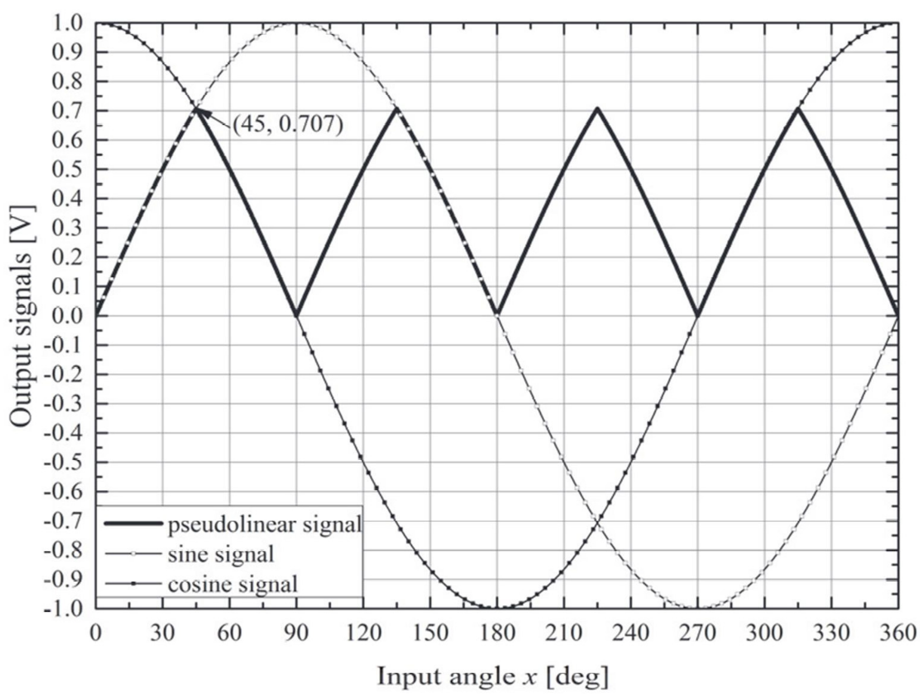
Figure 1. Testing scheme of the proposed linearization system

Measured angle x [rad]	A: $\sin(x)>0$	B: $\cos(x)>0$	C: $\cos(x)>\sin(x)$	D: $\sin(x)+\cos(x)>0$	D_2	D_1	D_0	Output signal
0-$\pi/4$	1	1	1	1	0	0	0	$+\sin(x)$
$\pi/4$-$\pi/2$	1	1	0	1	0	0	1	$+\cos(x)$
$\pi/2$-$3\pi/4$	1	0	0	1	0	1	0	$-\cos(x)$
$3\pi/4$-π	1	0	0	0	0	1	1	$+\sin(x)$
π-$5\pi/4$	0	0	0	0	1	0	0	$-\sin(x)$
$5\pi/4$-$6\pi/4$	0	0	1	0	1	0	1	$-\cos(x)$
$6\pi/4$-$7\pi/4$	0	1	1	0	1	1	0	$+\cos(x)$
$7\pi/4$-2π	0	1	1	1	1	1	1	$-\sin(x)$

Table 1. Signals and Bits Generated in the Proposed Linearization Circuit



(a)



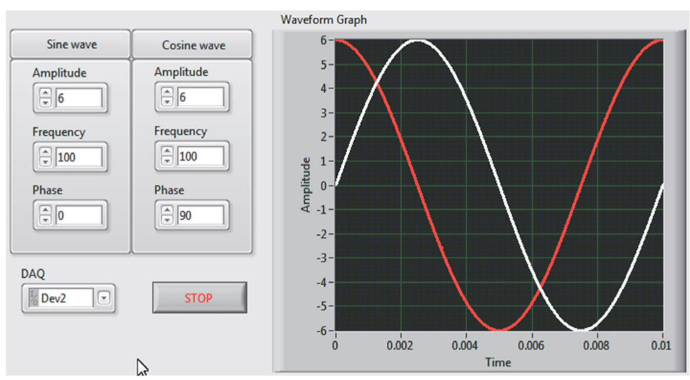
(b)

Figure 2. (a) Electrical scheme of the linearization circuit used for pseudo-linear signal generation, (b) Output pseudo-linear signal (bolded line)

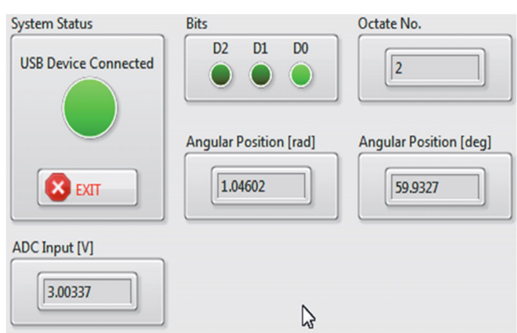
The octant to wich the current value of the measured angle belongs is represented by the bits D_2, D_1 and D_0. Also, these bits are intended for the control of the analog 8-to-1 multiplexer, as shown in Figure 2*a*. The waveforms of sine, cosine and pseudo-linear signal are shown in Figure 2*b*. In Table 1 are given logical values of *A, B, C* and *D* digital signals obtained at the comparators' outputs, the bits D_2, D_1 and D_0 and the waveforms of the output signal related to the current octant. It can be observed that in the measurement range of 2Â [rad] the pseudo-linear signal represents a combination of the most linear parts of the following signals: *sin*(*x*), *cos*(*x*), - sin(*x*) and -cos(*x*). As shown in Figure 2*a*, signals -*sin*(*x*) and - *cos*(*x*) are generated in the linearization circuit, and together with the input signals sin(*x*) and cos(*x*) are brought to the inputs of the analog 8-to-1 multiplexer. Which signal will be available at the output of the analog multiplexer depends on the corresponding octant of the current angle value *x*, i.e. it depends on the combination of bits D_2, D_1 and D_0.

In order to obtain a monotonically rising static transfer function of the complete measurement system (including position encoder, linearization circuit and the 10-bit ADC of the MCU), it is necessary to perform the inversion of ADC output bits when the current angle value *x* belongs to even octants, because in these octants the slope of the pseudo-linear signal waveform is negative. Since D_0 has a logical value of 1 in even octants, the most convenient manner to perform the aforementioned inversion is to bring the output bits of the ADCA/D converter together with D_0 to the inputs of ten logical XOR circuits. In comparison to the bits D_2, D_1 and D_0, the 10-bit ADC output bits are of less significance (weight).

For example, if the current value of the measured angle *x* belongs to the octant spanning from π to 5π/4 [rad], at the output of the multiplexer will be obtained the most linear part of the signal -*sin*(*x*) (see the last column in the Table I and see the Figure 2*b*, while the coding bits for this octant are **1 0 0**. Since the signal -*sin*(*x*) has only positive values for this octant and has the same shape and slope as the signal *sin*(*x*) in the range from 0 to π/4 [rad], the inversion of ADC output bits is not necessary. In the following octant (from 5π/4 to 6π/4), the pseudo-linear signal is represented by signal -*cos*(*x*), which has the same shape, but the negative slope in comparison to the signal *sin*(*x*) in the range from 0 to π/4 [rad]. In this case, the inversion of ADC output bits needs to be performed.



(a)



(b)

Figure 3. (a) Front panel of the VI used for sine and cosine signal simulation; (b) Front panel of the VI used for calculation and displaying of angular position measurement results

Figure 3*a*, the front panel of the virtual instrument, designed to generate signals from the encoder output, is shown. This virtual instrument offers the possibility of adjusting the amplitude, phase and frequency of sine and cosine signal in accordance with the rotating speed of the observed object whose angular position is measured (it is assumed that the speed of rotation, in the observed time interval, is constant). The cosine signal is obtained by phase shifting of the sine signal (with the same amplitude and frequency) by À/2 [rad]. The generated signals are brought to the designated inputs of the proposed linearization system over the CB-68LP connecting block and the PCI-6251 multifunction acquisition card. Fig. 3*b* shows the front panel of the virtual instrument designed to calculate and display the angular position after the linearization is finished. The virtual instrument determines the angular position x [rad] based on the values of bits D_2, D_1 and D_0 (which define the current octant number n), and on the basis of the voltage u [V] that is brought to the 10-bit ADC input. In precise, the following expressions are implemented in the virtual instrument: when the angle value x belongs to an odd octant:

$$x[\text{rad}] = (n-1)\cdot\frac{\pi}{4} + \arcsin\left(u[\text{V}]\right),\ n{=}1{,}3{,}5{,}7, \tag{4}$$

and when the angle value x belongs to an even octant:

$$x[\text{rad}] = n\cdot\frac{\pi}{4} - \arcsin\left(u[\text{V}]\right),\ n{=}2{,}4{,}6{,}8. \tag{5}$$

The printed circuit board (PCB) of the proposed linearization system, consisted of the linearization circuit and the MCU, is shown in Figure 4. The linearization circuit is realized using: two integrated circuits LM2903P, each of which has two comparators, integrated circuit CD4049UBE with six logical inverters, integrated circuit CD4030BE with four logical XOR circuits, integrated circuit LM224N with four operational amplifiers, DG408DJ multiplexer 8-to-1 and the PIC18F2550 MCU with the built-in multi-channel 10-bit ADC.

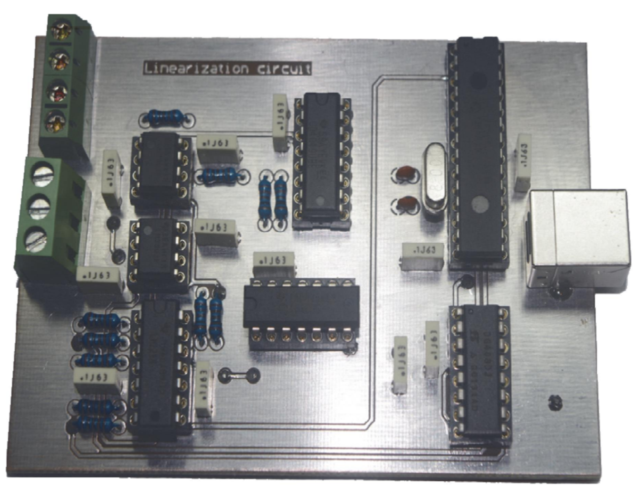
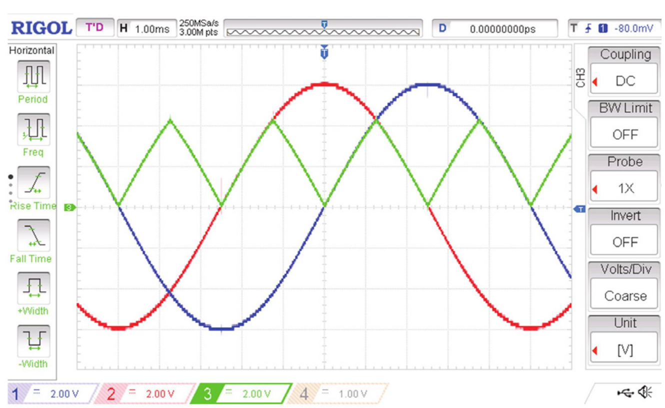
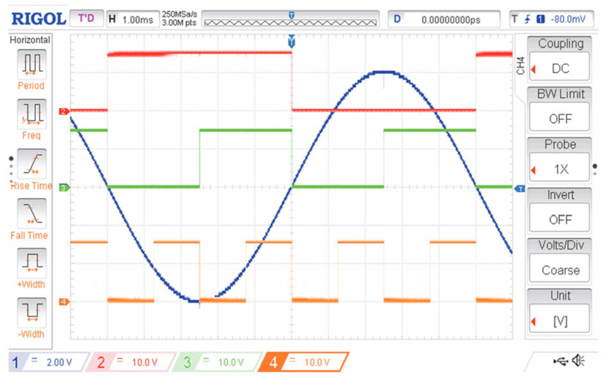


Figure 4. PCB of the proposed linearization system

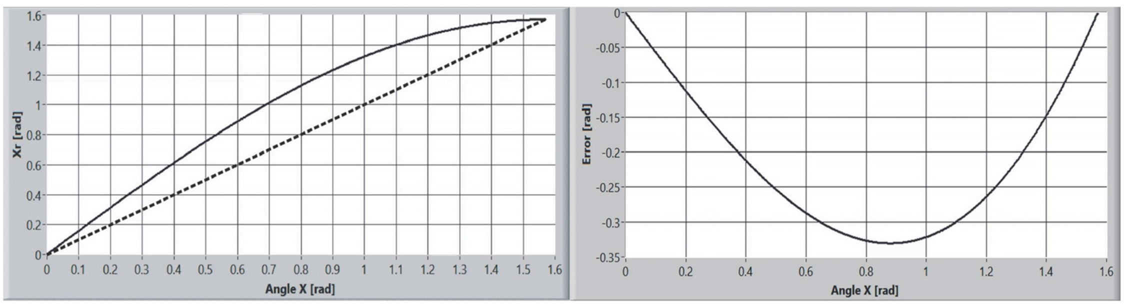


(a)

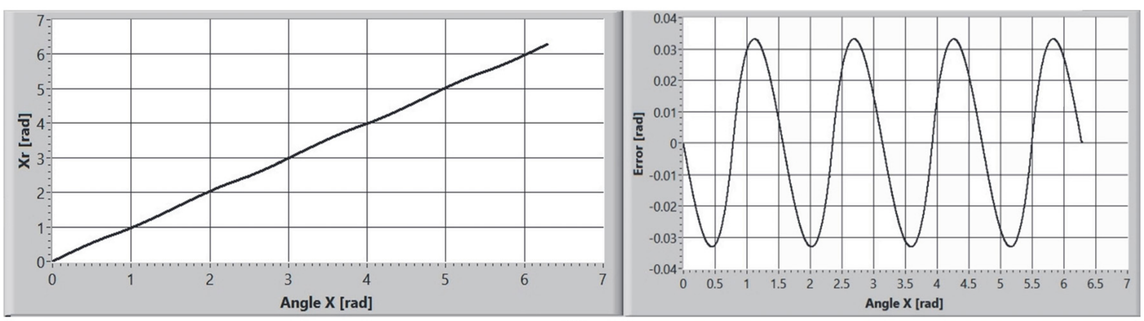


(b)

Figure 5. (a) sin(x), cos(x) and pseudo-linear signal; (b) Bits D_2, D_1 and D_0



(a)



(b)

Figure 6. Static transfer function of the measurement system and the absolute measurement error: a) For the range from 0 to π/2 [rad], without linearization, b) For the expanded range from 0 to 2π [rad], after the linearization is performed

In Figure 5*a*, the screen of the four-channel oscilloscope is shown when to the oscilloscope inputs are brought the following signals: sin(x) (blue), cos(x) (red) and the pseudolinear signal (green). When these signals are compared with the corresponding signals shown in Figure 2*b* (theoretical, i.e. expected signals' waveforms), a complete match is noticed.

The values of bits D_0 (orange), D_1 (green) and D_2 (red), in the range from 0 to 2π [rad], are shown in Figure 5*b*. By observing the pseudo-linear signal shown in Figure 5*a*, it can be noticed that its amplitude is smaller than the amplitude of the sine and cosine signal, i.e. it is equal to the value of $sin(\pi/4)\cdot A = cos(\pi/4)\cdot A \approx 0.707\cdot A$, where A represents the amplitude of the sine and cosine signal. In this manner, the input range of the 10-bit ADC is narrowed down.

To summarize, the application of the proposed linearization system increased the position encoder measurement resolution by three bits, while at the same time reduced the maximal absolute error by ten times. The maximal absolute measurement error before the linearization was Δx_{max}=0.3307 [rad], and after the linearization it is Δx_{max} = 0.0342 [rad]. These values can be seen in Figure 6 which, in addition to the dependence of the absolute measurement error on the measured angle, shows the static transfer function of the measurement system before (Figure 6*a*) and after the linearization (Figure 6*b*).

3. Conclusion

In this paper a cost-effective and simple linearization system used for angular position encoder resolution and accuracy increase, was presented. The proposed linearization system is consisted of the linearization circuit and the PIC18F2550 MCU with the built-in 10-bit ADC, implemented on the same PCB. By processing the nonlinear signals, obtained at the position encoder output, with the proposed linearization circuit, more linear resulting signal, so-called pseudo-linear signal, is obtained. In addition to the pseudolinear signal, the linearization circuit generates three bits used for coding of an octant, $\pi/4$ [rad] wide, to which the current value of the measured angle belongs.

One additional benefit of conducting the proposed linearization process, besides resolution increase for three bits and lower measurement error, reflects in the fact that in order to measure the angle it is enough to digitize the sine voltage in the range from 0 to $\pi/4$ [rad] using the 10-bit ADC, and have the information about the current octant (bits generated by the linearization circuit). In this manner the cost-effective and linear measurement system for determining the angular position of rotating objects, with three bits higher resolution and ten times smaller measurement error, is obtained.

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