ISSN 1726-5749

SENSORS & TRANSDUCERS

vol. 89
3/08

Smart Sensors and Systems

International Frequency Sensor Association Publishing

IFSA

IFSA

Sensors & Transducers

Volume 89
Issue 3
March 2008

www.sensorsportal.com

ISSN 1726-5479

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA). Available in electronic and CD-ROM.

Sensors & Transducers Journal

Contents

Volume 89
Issue 3
March 2008

www.sensorsportal.com

ISSN 1726-5479

Research Articles

Use of Smart Sensors in the Measurement of Power Quality
A. Moreno-Muñoz, and J. J. G. de la Rosa 1

A Multi-Channel, High-Precision Sensor Interface for Low-Power Applications – ZMD21013
Marko Mailand 10

Studying of a Tunneling Accelerometer with Piezoelectric Actuation and Fuzzy Controller
Ahmadali Tahmasebi Moradi, Yousef Kanani, Behrouz Tousi, Asadollah Motalebi, and Ghader Rezazadeh 17

Control of Neutralization Process Using Soft Computing
G. Balasubramanian, N. Sivakumaran and T. K. Radhakrishnan 30

Artificially Controlling the Limb Movement of Robotic Arm Using Machine Interface with EMG Sensor
Govind Singh Patel, Amrita Rai and Dr. S. Prasad 39

Active Vibration Control of a Flexible Structure Using Piezoceramic Actuators
J. Fei 52

Analysis and Implementation of Nonlinear Transducer Response over a Wider Response Range
Sheroz Khan, AHM Zahirul Alam, Syed Masrur Ahmmad, TIJANI I. B., Muhammad Asraful Hasan, Lawal Wahab Adetunji, Salami Femi Abdulazeez, Siti Hana Mohammad Zaini, Siti Aminah Othman, Saman S. Khan 61

Leak Detection and Model Analysis for Nonlinear Spherical Tank Process Using Conductivity Sensor
P. Madhavasarma, S. Sundaram 71

Analytical and Fundamental Study of EMATs System
A. Doniavi, M. Eskandarzade, J. Malekani 77

A Modified Design of an Anemometric Flow Transducer
S. C. Bera and N. Mandal 83

A Novel Hybrid Binary Reconstruction Algorithm for Ultrasonic Tomography
M. H. Fazalul Rahiman and R. Abdul Rahim 93

Sensors & Transducers Journal, Vol. 89, Issue 3, March 2008, pp. 61-70

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

Analysis and Implementation of Nonlinear Transducer Response over a Wider Response Range

Sheroz Khan, AHM Zahirul Alam, Syed Masrur Ahmmad, TIJANI I. B., Muhammad Asraful Hasan, Lawal Wahab Adetunji, Salami Femi Abdulazeez, Siti Hana Mohammad Zaini, Siti Aminah Othman, Saman S. Khan

Dept of ECE, PO Box 10
Kuala Lumpur 50728, Malaysia
E-mail: zahirulalam@iiu.edu.my, rafiq@iiu.edu.my, khaifa@iiu.edu.my

Received: 21 February 2008 /Accepted: 17 March 2008 /Published: 24 March 2008

Abstract: In today's automation systems transducers are making core elements in the instruments and the circuits used for measurement, control and industrial applications. The task of a transducer is to reproduce a physical quantity as an electrical signal which with the help of conditioning circuits, is transformed into a form that suits a corresponding ADC requirement before a digital equivalent output of the required physical quantity is produced. In the most ideal cases a digital quantity is a true replica of the physical quantity when the transducer has got a linear response. However, in most of the cases the transducers characteristics are nonlinear, and hence at very points along the whole range of the transducer characteristics, the corresponding digital output is an exact replica of the concerned physical parameter. This work is about how a physical read more accurately in the case of nonlinear sensor characteristics, and then a microcontroller is programmed with the same technique while reading from an input over the entire range. The data of the microcontroller reading shows very closely matched with the actual sensors response. Further, the reading error is considerably reduced to within 10 % of the actual physical which shows the utility of the technique in very sensitive applications. *Copyright © 2008 IFSA.*

Keywords: Nonlinear transducer response, Automation systems transducers, Transducers characteristics

1. Introduction

Being fundamental blocks of data acquisition, transducers are used in all the circuits and instruments for measurement and control in industrial applications, scientific research and development. In all of the latter systems, the principal device is the microcontroller. The microcontroller functions on signals that have already been converted to their digital equivalent [1].

Being an integral part of the sensor-based systems; the ADC works on a principle for converting an analog signal of a physical quantity into its equivalent digital output. The resulting digital quantity is a true equivalent of the signal concerned for a linear sensor response. However, almost all transducers are with nonlinear response, thus, providing a non-accurate linear digital equivalent. The error-prone digital output leads to error-loaded readings [2-3]. Some applications seem to be working fine with errors of tolerable levels, however, in other applications, where the tolerance level is narrow, small errors shoot up the system beyond the acceptable levels.

Several techniques for solving the non-linearity issue have been proposed, in one very instance not only have the nonlinearity issues been addressed, but furthermore, the hardware solution implementation has been suggested in the form of piecewise linear ADC [4]. In another case a Pulse-Width-Modulated output solution is suggested where errors obtained are compared with least-mean-square (LMS) method [5].

The aim of this paper is to further analyze the issue of transducers' linearization by taking a case study of a pressure sensor. The piecewise linearization curve illustrated attempts to clarify that it is an accurate line-of-best-fit for the analog curve under consideration. Hence, the numerous number of linear segments. The same technique is further demonstrated by suggesting a hardware that translates the lower and upper ends of a given segment into the starting and closing ends for the ADC, thus, ranging the ADC over a linear segment (or sub-sensor) of the entire sensor characteristics. Evidently, the results obtained match the actual curve.

The hardware implementation is credited with the benefit that it could be constructed from discrete components, thus, avoiding the need of making a custom-built special PWLADC. The results obtained are compared with the contemporary research in this field. Furthermore, it also attempts to highlight how this work differs from previous research work in terms of its hardware implementation approach. This paper also provides a way of understanding technical skills one must require in an attempt for a technician solution of an engineering problem avoiding the complicated procedures of industrial approaches.

2. Statement of the Problem

Almost all the sensor response curves non-linear, that is, the sensor output does not follow linearly its physical input, so the measurement made is sure to be with errors. The solution of the of nonlinearity is a challenging task in applications such as controlling temperature in oil refinery for partial distillation of crude oil, as such application demands high accuracy of measurement, even if not demanding high data rate.

In view of the need for accurate representation of the parameter under investigation, many circuits and techniques have been proposed to provide linearization of transducer outputs, the three major ones appeared in literature are: by the use of nonlinear analog signal conditioning, correction based on digital signal processing, and nonlinear analog-to-digital A/D converters.

This work is based on the approach which is a mix of nonlinear A/D converters and piece-wise linear (PLADC), which will dynamically adjust to the nonlinear characteristic.

The aim of this work is to make a comparative analysis of the performance of these techniques under varying conditions, and to obtain a hardware implementation of an optimum number of segments for a given response curve, making it ideal for an ADC working linearly between a pair of consecutive break points of a segment.

3. Nonlinearity Related Errors

A sample characteristic sensor curve is represented as a series of straight line segments joined together at points A to C over the entire range (Fig. 1).

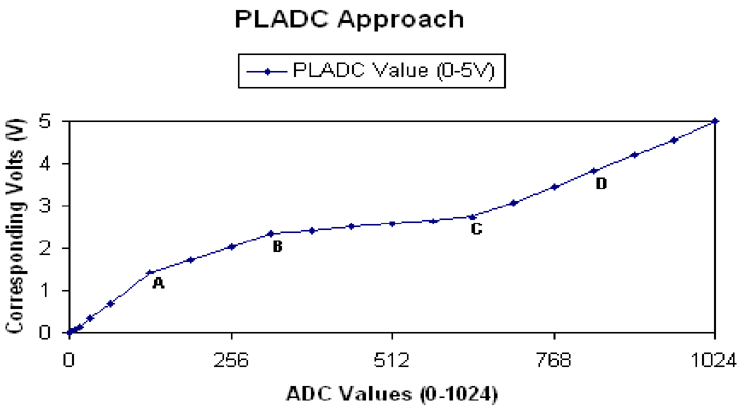

Fig. 1. Showing Sensor Curve Series of Straight Lines Joined Together at Break Points.

The error plot (Fig. 2) is an indication if the said implementation can be used for a particular application.

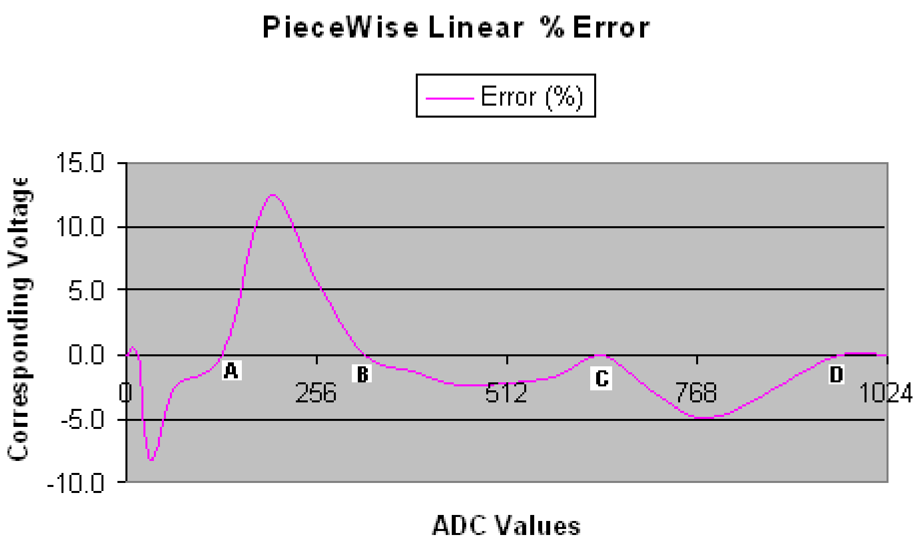

Fig. 2. % Error is Reaching Minimum at a Breakpoint.

Another nonlinear characteristic curve for airflow transducer is shown in Fig. 3, which has been obtained with Least Mean Square method as function of supply pressure (p.s.i).

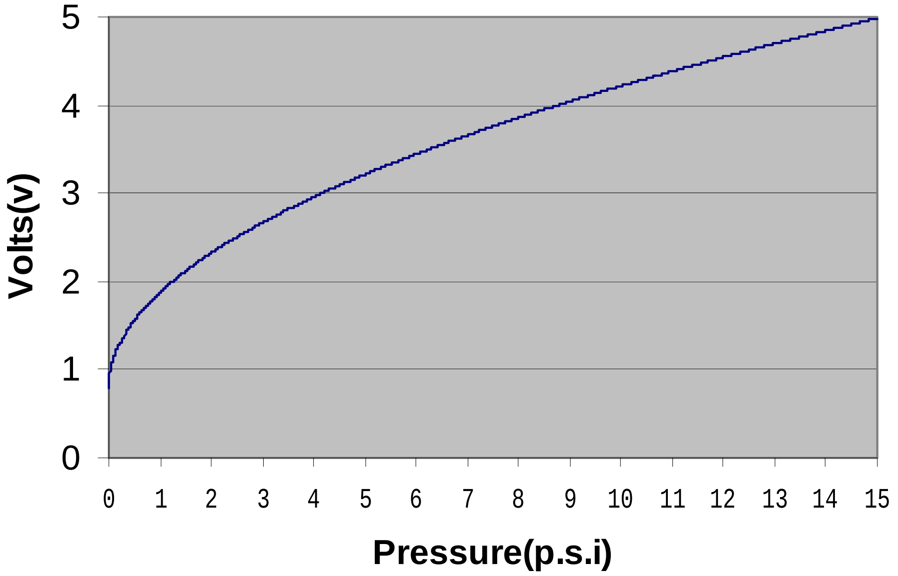

Fig. 3. Airflow Transducer Characteristics.

The nonlinear curve is segmented into an appropriate number of straight lines (four in Fig. 4), and errors analysis for above curve is shown in Fig. 5.

It is clear the error is near to 20 % in the first segment where the curve shows to be highly nonlinear, while it is almost very low in the last segment where the segment fits to the curve more closely.

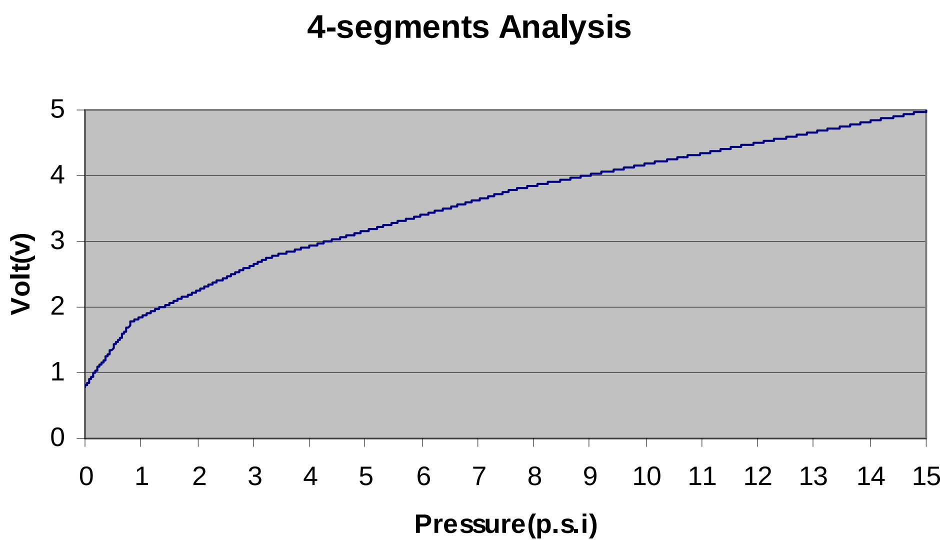

Fig. 4. Segmentation of Curve into four Segments.

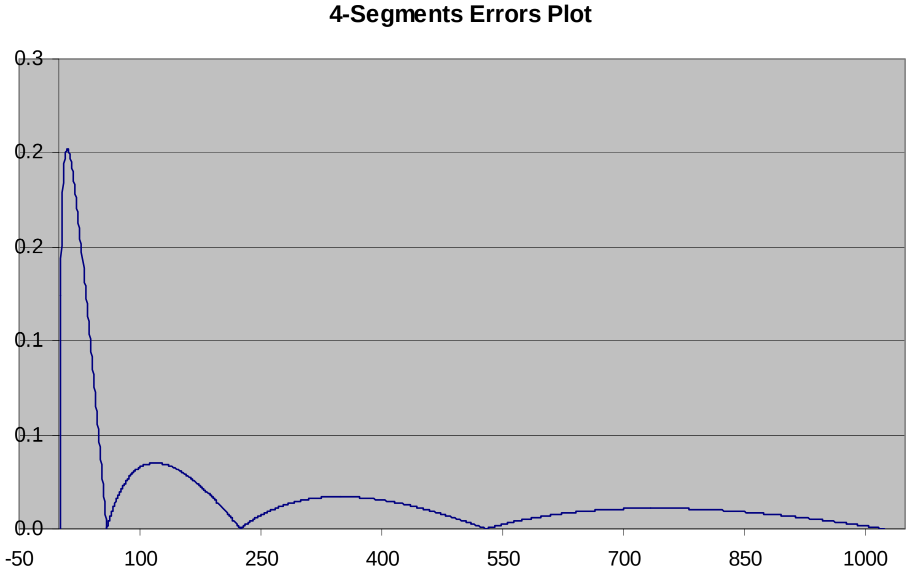

Fig. 5. Four Segments Error Analysis.

4. PIC16f877-Based Implementation

The Analog-to-Digital Converter (ADC) approximates a continuous-time analog signal to a 'line of best fit', thus, providing the prior signal with a digital linear curve of one approximate gradient (with reference to Series1 Fig. 6)

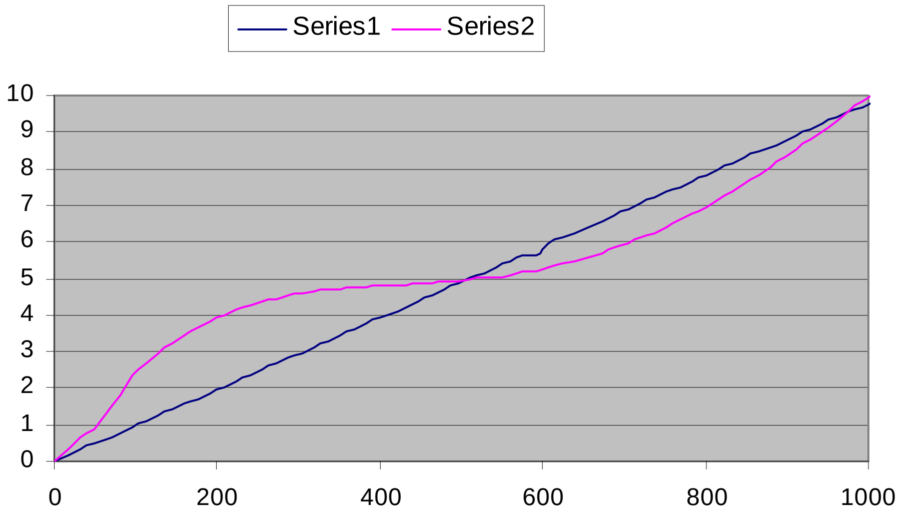

Fig. 6. ADC Reads Actual Nonlinear Curve Linearly.

The latter uncomplicated approximation of an analog signal, however, results in a wide range of errors (-60 % ≤ Value deviation ≤ 15 %) with respect to the deviation from the exact value (With reference to Fig. 7). The cause of such error in value is due to the sole reason that no analog curve can be represented as a linear curve of one single gradient, else it is sure to lead to inaccurate readings.

The said inaccuracy of the linear signal can be corrected by slicing the initial analog signal into a sequence of straight line segments. The gradient of these intervals are then calculated and represented by short linear curves.

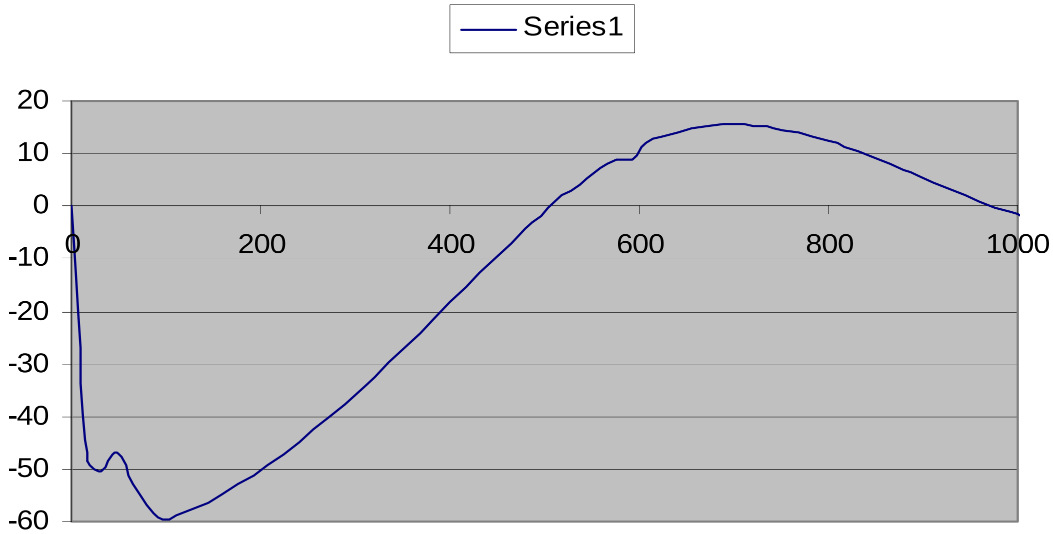

Fig. 7. Error Plot of Nonlinear Response Read Linearly.

The error with number of segments has been shown to be near 20% for 4-segment approximation, which reduces to 15% in the case of eight segments, and ends up as reduced to 13% for twelve segments (Fig. 8).

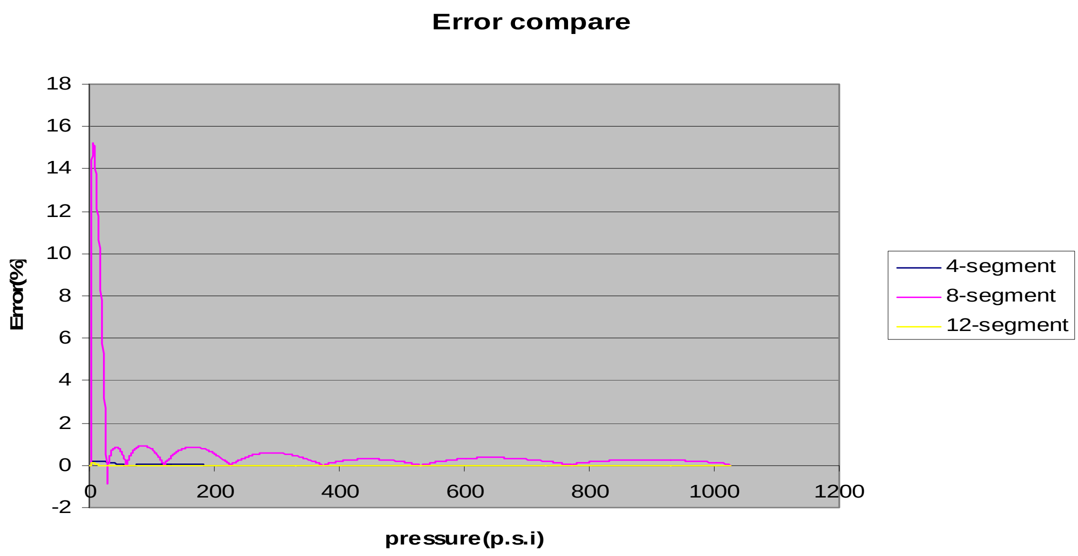

Fig. 8. PLMADC Error Correction.

Having done this for the entire analog signal, the linear curves are assembled together at the breakpoints to form a multi-gradient linear curve, hence, replacing the previous mono-gradient curve (Fig. 9). This proposed segmented signal reduces the error range with respect to original value deviation (-9 % ≤ Value deviation ≤ 1 %). Markedly, one can conclude that a decrease in the analog signal interval results in a lower error range. The larger the interval between two consecutive breakpoints, the wider will be the error range.

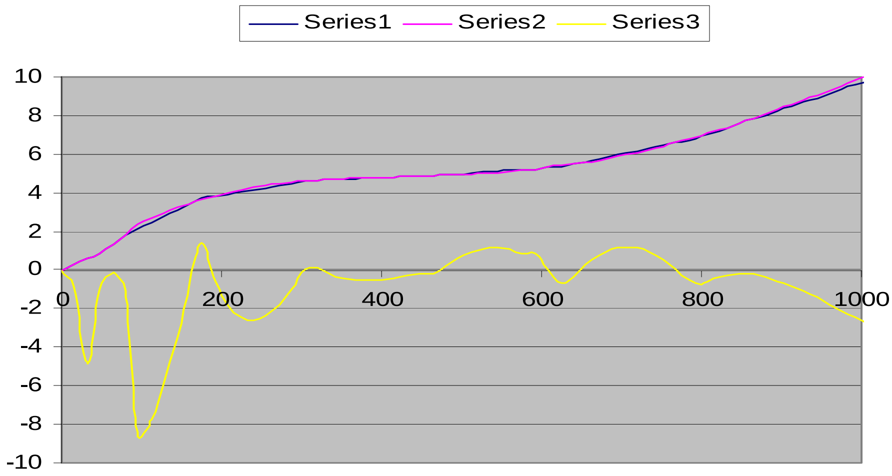

Fig. 9. PIC-Based Sensor Response and the Error Range.

5. Suggested Hardware Implementation

As it appears the suggested need to consist of – (i) a resistor divider for setting up voltage ranges over which the ADC used is to work linearly, (ii) a multiplexer for choosing a value of the input variable from which an ADC has to start. Starting an ADC from a given break point is accomplished with a circuit like the one shown in Fig. 10.

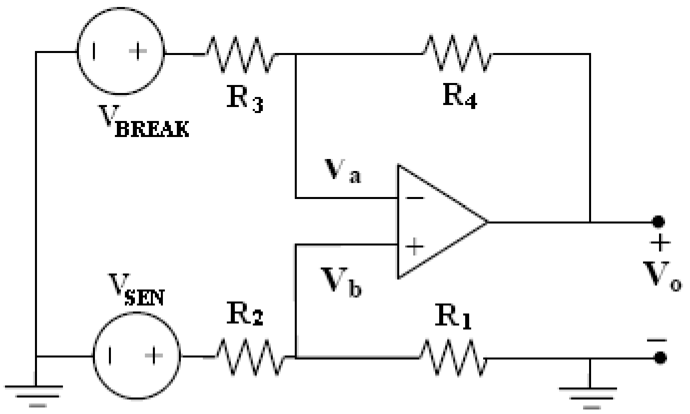

Fig. 10. Offset Adjustment Circuit Starting ADC from Lower Break Point.

It can be shown that the output voltage is given by

$$V_o = \left\{ (1 + \frac{R_3}{R_4})(\frac{R_1}{R_1 + R_2})V_{SEN} - \frac{R_4}{R_3}V_{BREAK} \right\},$$

where the ratio $\frac{R_4}{R_3}$ is a deciding factor in setting the lower end of a break point for a given piece of line segment. The input is voltage is applied to the positive inputs of a chain of OP AMP, which are already having voltages applied to their negatives inputs equal to the successive values of breakpoints voltages (Fig. 11). Thus the above circuit is used to apply the lower breakpoint voltage to V_{BREAK} value when V_{SEN} is ranging over a given piece of segment. Another circuit is used to decided first which one of the available segments V_{SEN} is ranging over, and then another digital logic circuit is used to pass V_{BREAK} and V_{SEN} on to two input of the circuits similar to the above with slope equal to the slope of the segment concerned. The results obtained with the above are plotted in Fig. 11.

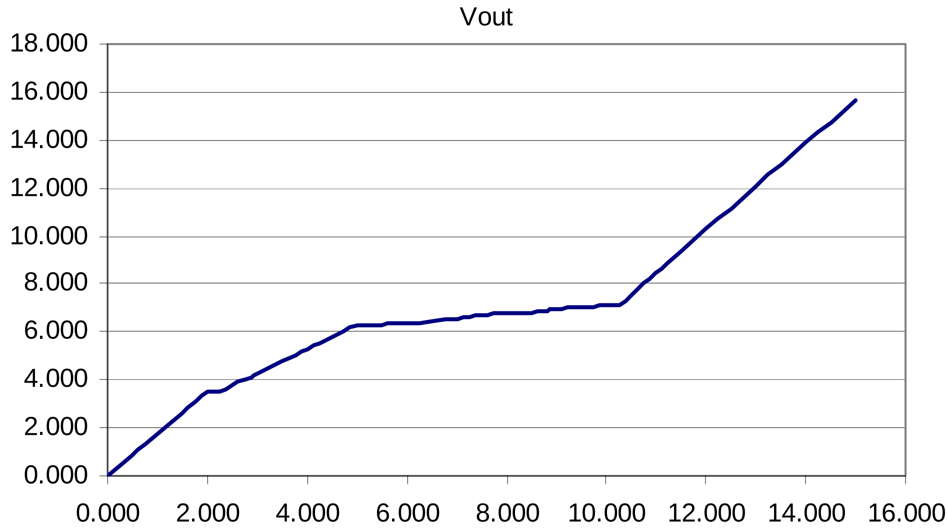

Fig. 11. Hardware Implementation Results Plot.

6. Conclusions

The transducer response characteristics have been analyzed, and the resulting errors in reading these sensors directly have been shown. The analysis and simulation carried out so far on nonlinearity issues show that a piecewise nonlinear method can be used to reduce the error of nonlinearity to a reasonable degree of accuracy. Also, the results show that better results could be better with the increase of the number of segments a given response curve is divided into.

The implementation involves software as well hardware—the former is done by programming a microcontroller (PIC16F877, C program listing given in APPENDIX I) and the results show a reduction in inaccuracy from 60 % to 10 %, while the later results show an inaccuracy of -10 % to 8%. The hardware and software implementation match up considerably while giving a flexibility of the implementation of using technician (or the programmer) expertise, depending which one of the two skilled professionals are available.

References

[1]. C. D. Johnson and H. Al. Richeh, Highly accurate resistance deviation to frequency converter with programmable sensitivity and resolution, *IEEE Transactions on Instrumentation and Measurement*, Vol. IM-35, 1986, pp. 178–181.

[2]. D. Patranabis, S. Ghosh, and C. Bakshi, Linearizing transducer characteristics, *IEEE Transactions on Instrumentation and Measurement*, Vol. 37, Mar. 1988, pp. 66–69.

[3]. G. Bucci and C. Landi, Metrological characterization of a contactless smart thrust and speed sensor for linear induction motors testing, *IEEE Transactions on Instrumentation and Measurement*, Vol. 45, Apr. 1996, pp. 493–498.

[4]. Giovanni Bucci, Marco Faccio, and Carmine Landi, New ADC with Piecewise Linear Characteristic: Case Study—Implementation of a Smart Humidity Sensor, *IEEE Transactions on Instrumentation and Measurement*, Vol. 49, No. 6, Dec. 2000.

[5]. J. M. Dias Pereira, O. Postolache, and P. Girão, PWM-A/D conversion: a flexible and low-cost solution for transducer linearization, in *Proc. ISA/IEEE SIcon'01*, Rosemount, IL, Nov. 2001, pp. 258–263.
[6]. J. M. D. Pereira, O. Postolache and P. M. B. S. Girao, A Digitally Programmable A/D Converter for Smart Sensors Applications, *IEEE Transactions on Instrumentation and Measurement,* Vol. 56, No.1, Feb. 2007.

Appendix I

```
/*******************************************************
*                                                      *
*         PIECEWISE_LINEAR_ADC.c                       *
* This program reads an analog input from the input    *
* port AN0 (port A0) and converts it to a linearized   *
* reading using the piecewise linear ADC characteristic *
* equations.                                           *
*                                                      *
 *******************************************************/

#include <16F877A.h>
#fuses HS,NOWDT,NOPROTECT,NOLVP
#device adc=10
#use delay(clock=10000000)
#use rs232(baud=9600, xmit=PIN_C6, rcv=PIN_C7, parity=n, bits=8, stream=MONITOR)
#include <stdlib.h>

void main() {

  int16 adc_reading;   //potientiometer reading (0 - 1023)
  float volt_reading;  //initial voltage value (0 - 10v)
  float PLADC_volt;    //PLADC value (0 - 10v)
  float final_volt;    //Voltage value (0 - 5v)

  set_tris_a(0x01);

  setup_adc_ports(AN0);
  setup_adc( ADC_CLOCK_DIV_16);

  while(1)
  {
        set_adc_channel(0);                  // select AN0
        delay_us(40);
        adc_reading = read_adc();
        volt_reading=(float)adc_reading*10/1023;

        if(volt_reading > 0.00 && volt_reading <= 0.46)
          PLADC_volt = 1.925*volt_reading;
        if(volt_reading > 0.46 && volt_reading <= 0.86)
          PLADC_volt = 2.9167*volt_reading-0.49585;
        if(volt_reading > 0.86 && volt_reading <= 1.66)
          PLADC_volt = 2.0769*volt_reading+0.1827;
        if(volt_reading > 1.66 && volt_reading <= 2.98)
          PLADC_volt = 0.6977*volt_reading+2.5101;
        if(volt_reading > 2.98 && volt_reading <= 4.55)
          PLADC_volt = 0.1633*volt_reading+4.13;
        if(volt_reading > 4.55 && volt_reading <= 6.12)
          PLADC_volt = 0.3137*volt_reading+3.4437;
```

```
        if(volt_reading > 6.12 && volt_reading <= 7.72)
          PLADC_volt = 0.9020*volt_reading-0.1779;
        if(volt_reading > 7.72 && volt_reading <= 10.00)
          PLADC_volt = 1.4167*volt_reading-4.167;


        final_volt=PLADC_volt/2;

        printf("\n\rADC reading: %ld \n\r", adc_reading );
        printf("\n\rLinear voltage reading: %lf \n\r", volt_reading);
        printf("\n\rPLADC Conversion: %lf \n\r", PLADC_volt);
        printf("\n\rFinal voltage reading: %lf \n\r", final_volt);

  }

}
```

Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because it is an open access, peer review international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per annual by International Frequency Association (IFSA). In additional, some special sponsored and conference issues published annually.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

Submission of papers

Articles should be written in English. Authors are invited to submit by e-mail editor@sensorsportal.com 6-14 pages article (including abstract, illustrations (color or grayscale), photos and references) in both: MS Word (doc) and Acrobat (pdf) formats. Detailed preparation instructions, paper example and template of manuscript are available from the journal's webpage: http://www.sensorsportal.com/HTML/DIGEST/Submition.htm Authors must follow the instructions strictly when submitting their manuscripts.

Advertising Information

Advertising orders and enquires may be sent to sales@sensorsportal.com Please download also our media kit: http://www.sensorsportal.com/DOWNLOADS/Media_Kit_2008.pdf