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A Novel Technique for the Temperature Dependent Studies of Materials Using a Microwave Resonant Cavity

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Abstract **--This study presents a linearization technique for transducers by using software solutions programmed into a microcontroller. Existing data acquisition systems linearize nonlinear transducer characteristics in real time using analog linearizing circuitry, which are susceptible to errors due fluctuations in power supply voltage, temperature, and interference from correlated and uncorrelated noise sources in the system. The goal of this work is to replace analog hardware techniques for linearization using software solutions provided by microcontrollers, which also has inherent capabilities for performing signal conditioning and data acquisition among others. The methodology for linearization is the piecewise-linear software approximation technique using the one-sixth and five-sixth operating points on each segment, and results show an improvement over the end point approximations. This technique is successfully used in an existing microcontroller to monitor the temperature of a microwave resonant cavity. The resonant cavity is used to study the microwave dielectric response of different materials as a function of temperature and frequency.**

Index Terms: **Microcontroller, Data Acquisition, linearization, offset approximation, microwave resonant cavity, microwave dielectric response.**

I. INTRODUCTION

Transducers typically have input-output characteristics that are partially or wholly nonlinear over its operating range. In this work we choose such a transducer to show how to linearize nonlinear transducer characteristics using a software technique programmed into the microcontroller. The software solution provides a distinct advantage over analog linearizing circuitry because analog circuits are susceptible to errors due fluctuations in power supply voltage, temperature, and interference from correlated and uncorrelated noise sources in the system [1]. The motivation to use of microcontrollers in this work is because they are quickly becoming a basic building block for data acquisition and control applications in research and industry. While today's microprocessors are designed to support high-level languages for general-purpose applications, microcontrollers are optimized for data acquisition and control applications [2]. Another added advantage is the availability of signal conditioning features, which serves to eliminate a significant number of discrete components required in data acquisition applications.

Nonlinear transducer characteristics can be linearized in real time by hardware circuits with matching input-output equations. Linearization can also be accomplished by using software programmed into a microprocessor or microcontroller. This technique eliminates the need for trimming required by analog linearizing circuitry [3]. Software solutions include look-up tables (memory intensive), power series expansions, or piecewise-linear approximations. This work will feature the piecewise-linear software approximation technique because transducers typically have a slightly bow-shaped characteristic (bow up or down) [4], and accurate linear approximation transducer equation can be derived by connecting a straight line through the one-sixth and five-sixth operating points.

The upcoming sections will discuss microcontroller development platform for data acquisition systems; measurement system overview that utilizes the Type J thermocouple; microcontroller application in software design for linearization equations; and interfacing analog signals to the M68HC11 microcontroller.

II. MICROCONTROLLER DEVELOPMENT PLATFORM

The complete hardware for microcontroller based data acquisition systems are relatively simple to implement. The finished product consists of a sensor, support components, and a microcontroller IC (Integrated Circuit) with a “burned-in” dedicated software program.

The microcontroller development platforms are primarily printed circuit boards that contain, in addition to a microcontroller, a set of monitor programs stored in ROM chips, input-output (I/O) circuitry, and interfacing capabilities to a dumb (or smart) terminal. Terminal interfacing feature allows communications to the microcontroller over the RS-232 line. A complete development system contains at its core the development platform and the user provides transducer and signal conditioning circuitry to accommodate measurement of physical quantities. The circuitry necessary to develop a complete microcontroller-based acquisition system further requires the design of input circuitry to acquire data and output signals to fit the analog to digital converter (ADC). The design of such a system begins by first selecting a transducer to sense the physical quantity to be measured. In this work the Type J thermocouple is featured, and the transducer nonlinear characteristics is derived either from manufacturer’s data sheet [3] or from measured data. This data will was used to determine the thermocouple’s output at upper and lower limits for corresponding input temperature limits. Unfortunately as with many other transducers that rarely outputs values suitable for direct input into the microcontroller’s ADC, these limits are used to derive the signal conditioning circuitry (SCC) design equation. The typical SCC includes both span and offset adjustment or trims so that its output signal interfaces to the full input span of the microcontroller’s A/D controller to allow for maximum measurement resolution.

III. THERMOCOUPLE TRANDUCER EQUATIONS

A Type J thermocouple’s input-output characteristic seems reasonably linear by simple inspection of the thermocouple manufacturers reference table. However if the thermocouple were linear, ΔV_m (change in thermocouple output voltage) would be equal for each equal increase in thermocouple temperature, ΔT_m in the operation range of the transducer. The sensitivity or slopes $\alpha = \frac{\Delta V_m}{\Delta T_m}$, increases as temperature increases to indicate the upward bow-shaped nonlinearity of V_m vs. T_m over even a limited range of temperature values.

Since transducer data display a slightly bow-shaped characteristic (bow up or down), a more accurate linear approximation of transducer equation was derived by constructing a straight line through the one-sixth and five-sixth operating points. In using this method, the V_m vs. T_m graph does not pass through the origin but intercepts the vertical axis at V_{m_0}. For this reason it is called the offset linear approximation of the transducer characteristic and the following derives its equation:

$$\alpha = \frac{V_m^{5/6th.} - V_m^{1/6th.}}{T_m^{5/6th.} - T_m^{1/6th.}} = \frac{V_m - V_m^{1/6th.}}{T_m - T_m^{1/6th.}} \tag{1}$$

where

$$V_m = \alpha \times T_m - V_{m_0}$$

$$V_{m_0} = -\alpha T_M^{1/6th.} + V_M^{1/6th.}$$

For the Type J thermocouple considered in this work, the transducer offset approximation equation in the range of $0\,°C$ to $50\,°C$ is

$$V_m = 51.7\frac{\mu V}{°C}\times T_m - 8\mu V \qquad (2)$$

Since it passes through the origin, there is no offset term in the equation above. There are noticeable improvements over the endpoint approximation method, and was therefore selected for constructing a piecewise-linear graph to span the temperature range of $0\,°C$ to $500\,°C$ [4].

The signal conditioning must amplify the signal from the transducer to fill the 5.12V input span of the ADC in the microcontroller used in this work. For convenience, we chose a range for the signal conditioning circuit output V_0 of 0V to 5V to represent the Type J thermocouple output V_T of 0mV to 27.388mV. The SCC therefore has a gain of

$$\frac{\Delta V_0}{\Delta V_T} = \frac{(5-0)V}{(27.388-0)mV} = 182.6 \qquad (3)$$

and the SCC design equation is written by inspection as $V_0 = 182.6\times V_T$. In choosing an operational amplifier operating in the noninverting configuration for the SCC circuit, the hardware equation is [1]

$$\frac{V_0}{V_T} = \left(1+\frac{R_f}{R_i}\right) = 182.6 \qquad (4)$$

For an arbitrary choice of $R_i = 1\text{k}\Omega$, one can calculate $R_f = 181.6\text{k}\Omega$. This completes the analog interface design that will furnish data for the microcontroller programmer to write the linearization program.

III. *A Programming Linearization Equations*

The procedure for deriving the programming linearization equations is to first construct a graph for the Type J thermocouple nonlinear characteristics, V_m vs. T_m, over the problem's range of interest, i.e. $0\,°C$ to $500\,°C$. The graph was then divided appropriately into equal piecewise linear segments, and for this work segments of $100\,°C$ increments were chosen. Choosing more segments would give a better approximation at the expense of increased complexity of the software linearization program, memory space, and program execution time. The one-sixth and five-sixth operating points for each segment is located and the offset linear approximation equation of V_T vs. T_m was derived. The following table lists the data obtained from the manufacturer's data sheet for the Type J thermocouple.

Table 1:

Segment	**Temp. at** $\frac{1}{6}$ and $\frac{5}{6}$	$V_T \sim mV$	$\Delta V_T \sim mV$	**Slope in** $\frac{\mu V}{°C}$
$0\,°C$ - $100\,°C$	$\left.\begin{matrix}17°C\\83°C\end{matrix}\right\}66°C$	$\left.\begin{matrix}0.865\\4.347\end{matrix}\right\}$	3.482	$52.7\frac{\mu V}{°C}$
$100\,°C$ - $200\,°C$	$\left.\begin{matrix}117°C\\183°C\end{matrix}\right\}66°C$	$\left.\begin{matrix}6.195\\9.834\end{matrix}\right\}$	3.639	$55.1\frac{\mu V}{°C}$
$200\,°C$ - $300\,°C$	$\left.\begin{matrix}217°C\\283°C\end{matrix}\right\}66°C$	$\left.\begin{matrix}11.720\\15.383\end{matrix}\right\}$	3.663	$55.5\frac{\mu V}{°C}$
$300\,°C$ - $400\,°C$	$\left.\begin{matrix}317°C\\383°C\end{matrix}\right\}66°C$	$\left.\begin{matrix}17.27\\20.91\end{matrix}\right\}$	3.364	$55.2\frac{\mu V}{°C}$
$400\,°C$ - $500\,°C$	$\left.\begin{matrix}417°C\\483°C\end{matrix}\right\}66°C$	$\left.\begin{matrix}22.78\\26.44\end{matrix}\right\}$	3.655	$55.4\frac{\mu V}{°C}$

Since each temperature increment is for example (483-417)$°C$, the slope of each offset linear segment is calculated from $\Delta V_T\,/\,66°C$ and listed in column five of Table 1. Next the approximating equations was derived using

$$\alpha = \frac{V_T - V_m^{1/6th.}}{T_m - T_m^{1/6th.}} \qquad (5)$$

Using the method above, approximating equations are derived for each segment. The SCC applies a gain of 182.6 to the transducer circuit's out put V_T. The analog interface output V_0 is obtained by simply multiplying the V_T approximating equation by 182.6 and the results are tabulated in Table 2.

Table 2:

Linear Approximation Equation	**Valid in T_m Range**	**Valid in V_T Range**
$V_T = 9.63\frac{mV}{°C} \times T_m - 5.82mV$	0-100 $°C$	0-0.962V
$V_T = 10.06\frac{mV}{°C} \times T_m - 46.7mV$	100-200 $°C$	0.962-1.967V
$V_T = 10.13\frac{mV}{°C} \times T_m - 59.2mV$	200-300 $°C$	1.967-2.981V
$V_T = 10.08\frac{mV}{°C} \times T_m - 42.2mV$	300-400 $°C$	2.981-3.989V
$V_T = 10.12\frac{mV}{°C} \times T_m - 56.4mV$	400-500 $°C$	3.989-5.000V

The programming equations to be used in the microcontroller for each segment in Table 2 is found by solving its analog interface equation for T_m. For example the equation for the third segment, 200-300 $°C$ is

$$T_m = \frac{V_0 + 59.2mV}{10.13\frac{mV}{°C}}$$

for $V_0 = 1.967$ to 2.981V. In a similar fashion, equations are derived for each segment and tabulated in Table 3. Therefore, for a specific voltage V_0 entering the microcontroller and belonging to a particular segment of the piecewise linear graph, the equivalent temperature can be calculated and recorded.

Table 3:

If V_0 is Between	**Find T_m From**	**Segment**
0-0.962V	$T_m = \frac{V_0 + 5.82mV}{9.632mV / °C}$	0-100 $°C$
0.962-1.967V	$T_m = \frac{V_0 + 46.7mV}{10.06mV / °C}$	100-200 $°C$
1.967-2.981V	$T_m = \frac{V_0 + 59.2mV}{10.134mV / °C}$	200-300 $°C$
2.981-3.989V	$T_m = \frac{V_0 + 42.18mV}{10.08mV / °C}$	300-400 $°C$
3.989-5.000V	$T_m = \frac{V_0 + 56.42mV}{10.12mV / °C}$	400-500 $°C$

IV. INTERFACING TO THE M68HC11

This section describes how to interface analog signals to the M68HC11 microcontroller, and discusses programming requirements for performing data acquisition.

On the MC68HC11, the thermocouple is interfaced to the 8-bit input port called Port E that connects to the A/D converter on the microcontroller. Input range for this microcontroller is 0 to 5.12V. As discussed in the preceding section, the analog interface used in this work will scale the transducer signal of the Type J thermocouple to fit within the voltage span of the microcontroller. The A/D converter requires two reference-input voltages, i.e. the low reference voltage signal pin, V_{RL} and high reference voltage signal pin V_{RH}. It is recommended that these pins be connected through a low pass filter, however the MC68HC11 does come with a built in 0.01 μF capacitor for signal processing purposes. Using a resistor in series with the capacitor, the microcontroller is therefore capable of filtering out high frequency fluctuations in the power supply voltage, rendering more accurate readings. In addition, this eliminates the need for external components that act as a potential source of correlated noise within the data acquisition system.

The resolution of the M68HC11 is 8 bits which is equivalent to 20mV/1 bit over the ADC input range. This resolution is sufficient for most applications that use a microcontroller. The actual analog-to-digital conversion is accomplished by an on-board A/D converter and the results are put into one of the four result registers (ADR1-ADR4). Therefore, the user only has to write instructions for the CPU to read a result register to obtain the digital equivalent of the analog signal from the thermocouple. Although the microcontroller has 8 A/D channels, the result from a group of 4 channels (0-3 or 4-7) can be stored in the result registers at any one time. In this work, a single channel is used and the result of conversion is stored sequentially in registers ADR1-ADR4. Although a conversion result may be read at any time, it is necessary to allow the ADC sufficient time to make a conversion. For the MC68HC11, the ADC requires 32 clock cycles (equivalent to $16\mu s$ with a 2.0 MHz clock) to update one result register or a total of $64\mu s$ for the four registers. In order to allow for sufficient conversion time, the micro-controller interval timer was used to set the interrupt flag bit after $16\mu s$ or $64\mu s$ pre-specified time period.

Another issue that requires attention when interfacing analog signal to the microcontroller is its current handling capability. Typically the M68HC11 could handle 1mA on any of the 8 pins on the analog input Port E.

V. DIELECTRIC RESPONSE

It is very interesting to study the microwave dielectric response of materials as a function of temperature and frequency [5-7]. The dielectric behavior changes dramatically as a material goes through a phase change. The temperature of a microwave resonant cavity can be changed fairly easy, however, exercising precise control over the temperature is much more difficult. Without the temperature control system, it is difficult to get meaningful data of dielectric studies as a function of temperature because the temperature drifts rapidly. A feedback microcontroller system using a computer, a thermocouple, an electronic valve, and an interface device is used to monitor the temperature very precisely. The software linearization technique explained in this paper is used very successfully to drive the microcontroller which in turn monitors the temperature of the microwave resonant cavity. The purpose of this experiment is to program the microcontroller and monitor the temperature of the resonant cavity. The dielectric response of a material changes very rapidly near a phase transition temperature. It is extremely important to monitor the temperature as precisely as possible to measure the dielectric response accurately. The technique used in this experiment to drive the microcontroller seems to work very nicely to monitor the temperature of the microwave resonant cavity near phase changes.

VI. CONCLUSION

This study presented a linearization technique for the Type J thermocouple transducer using software solutions programmed into a microcontroller. It features the offset piecewise-linear approximation, which utilizes the one-sixth and five-sixth operating points on each segment. Generally our results have shown an improvement over end-point approximations. The use of the microcontroller in this work provided for a low-cost and dedicated system that is optimized for data acquisition applications. Also with the availability of signal processing features, the microcontroller automatically provides for low pass filtering which relaxes the need for external components that serve as potential noise source in data acquisition system.

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