METHODS OF ACCURATELY MEASURING CAPACITIVE RH SENSORS

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Abstract: The operation of Capacitive RH Sensors has been well described in the literature and is generally well understood. The electronic circuits used to measure these Sensors, on the other hand, have not been well described. The few published approaches typically provide poor performance – particularly over a wide operating range.

This paper first describes what is required and the problems associated with the 'classic' circuits. The paper further describes the work done by Veriteq Instruments over the past several years where a variety of measuring circuits/systems were evaluated.

It discusses the problems which are unique to an electronic insitu humidity measuring device which must accurately operate in a wide-range environment: <1% to > 95% RH and -40°C to +85°C. It concludes by describing how a familiar measurement approach was adapted for use in a small-sized very low power system and the calibration challenges associated with it.

Key words: Electronic Humidity Measurement Circuits

1. SYSTEM REQUIREMENTS

While some of the requirements for this system are unique to a long battery life (10 year) autonomous Data Logger, they do share many commonalities with other industrial RH measurement systems.

The Key Requirements for the RH measurement portion of this system are as follows:

− Low Energy - Consuming no more than 400μJ per RH measurement.
− A Wide operating range of -40 to 85°C and 0 to >95% RH with the Measuring Electronics contributing a total equivalent measurement error of less than 0.25% RH over the operating range of 0 to 70°C.
− No Net DC Voltage across the Sensor.
− Manufacturable with standard Printed Circuit Board (PCB) assembly processes.
− Standard Calibration requiring no more than 5 Data Points.
− Accommodate Application Specific Wide-Range Calibrations while maintaining overall accuracy.

Many of these requirements are interrelated and typically require compromise.

Although the energy consumption requirement is particularly stringent in this application, it does correspond to very low heat generation which is generally desirable for RH measuring systems. For example, at 70°C and 85% RH, a 0.1°C temperature rise could alone cause a measurement error of 0.4% RH.

When very low energy consumption is required, electronic circuits generally utilize high impedance techniques. High impedance circuits are, however, typically more vulnerable to leakage and contamination than their lower impedance counterparts. When high levels of moisture are present, even the very small levels of contamination present from the PCB assembly process can interfere with accurate operation of a high impedance measurement circuit.

Hermetic enclosures can isolate the electronics from the ambient humidity but are very expensive and do not block the wide operating temperature range. Conformal coatings help to keep contaminants directly off of the circuit, but are not effective as a moisture barrier.

In order to meet the measurement accuracy and calibration goals, the system would need to be both repeatable in its measurements as well as predictable on a unit to unit basis. If each unit provided significantly different raw (uncalibrated) values from the next, it could take a large number of data points to calibrate it.

2. SENSOR BASICS

Capacitive RH sensors have proven themselves to be a practical sensor technology in a wide variety of industrial applications.

In its simplest form, a capacitor is formed when two conductive plates are separated by an insulator (dielectric).
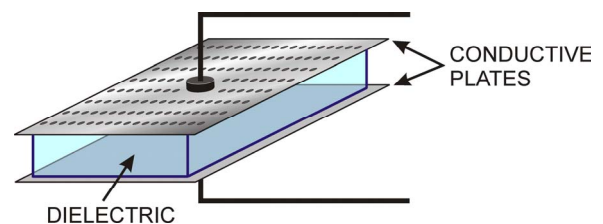

Figure 1 – Capacitor Structure

The electrical capacitance is defined by the area of the plates, the distance between them and the dielectric coefficient of the medium separating the plates.

In a Capacitive RH Sensor, the dielectric material is allowed to diffuse and absorb water vapor so that it equilibrates with the external environment. The 'dry' dielectric coefficient is significantly lower than that of water, and thus the electrical

capacitance increases as the dielectric absorbs water – reflecting the Relative Humidity of the surroundings.

From an electrical standpoint, however, these Sensors exhibit a relatively small change in capacitance over their measurement range. A capacitance change of 40 to 50pF over 0 to 100% RH with a 0% RH capacitance (C_{0RH}) of 100 to 200pF is not uncommon.

3. MEASUREMENT CIRCUITS

In industrial capacitive sensor applications, two general approaches are commonly used in the electronic measurement system: Oscillators and Charge-Based circuits.

3.1. Oscillator Based Approach

In this approach, the electrical capacitance of an RH sensor (C_{RH}) is used to set the frequency of an oscillator. As the RH (and thus the capacitance) changes, so does the oscillator frequency.

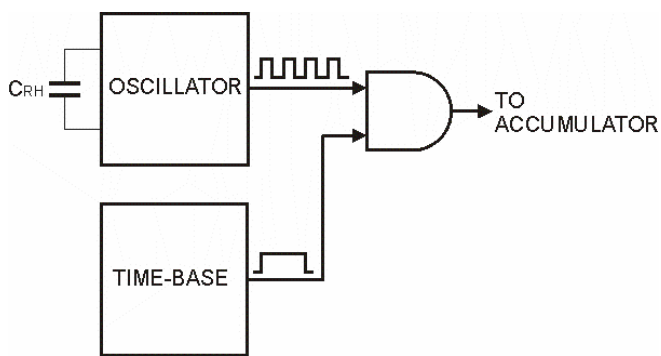This frequency, in turn, can be measured directly by a micro-controller.

Figure 2 – Oscillator Measurement Method

As shown in the figure, the Time-Base 'Gates' the oscillator into an accumulator which counts the number of cycles from the oscillator. This accumulated value is proportional to the oscillator frequency and thus C_{RH}.

When this approach is implemented with a Monolithic Timer, it can form the basis of a very simple RH measurement system and is a good choice for many lower-accuracy applications.

For optimal accuracy, the output frequency should change only as a function of the sensor capacitance, but this is not readily achieved.

Virtually all oscillators have some sensitivity to their operating voltage and while simple supply regulation may appear to provide a solution, a wide operating temperature will always result in some level of supply variation.

Temperature changes also have a direct affect on the oscillator itself - altering the values of passive components and the dynamic characteristics of active devices.

A variety of low power oscillator circuits were developed and evaluated as part of this project. A suitable combination of accuracy and low energy was not achieved. Higher speed devices minimized the effect of temperature on the oscillator frequency, but consumed too much energy. Lower oscillator frequencies minimized operating power and temperature effects but required a longer time to accumulate an adequate number of cycles from the oscillator and thus increased total energy. For example, an oscillator using a sensor with a C_{0RH} of 150pF and operating between 15 and 20 KHz would require a 500mS Time-Base Gate time for adequate resolution and could easily require 1.2mJ per measurement.

While it is technically possible to calibrate-out the temperature dependant variation, it was found that critical device parameters varied significantly from unit to unit. This would require an impractically large number of calibration points to be performed on each unit if the accuracy goals were to be met. Additionally, some factors (such as battery related aging) would vary over time and would introduce additional measurement errors.

3.2. Charge Based Approaches

Another common measurement method relies upon the ability of a Capacitor (RH sensor) to hold and transfer an electrical charge.

The Voltage present across a capacitor is proportional to the charge held in the capacitor.

$$V = Q/C \tag{1}$$

Where Q is the electrical charge stored in the Capacitor (Coulombs), C is the value of the Capacitor (Farads) and V is the Voltage across the Capacitor (Volts).

One measuring method relies upon a reference Capacitor (C_{REF}) being changed by a known Voltage Source (V_{REF}).
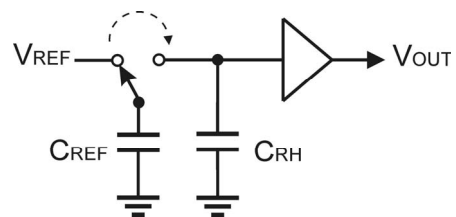

Figure 3 – Charge Based Measurement Method

C_{REF} is first charged to V_{REF} and then switched in parallel with C_{RH}. In an ideal system, the total charge would remain constant and by knowing the value of C_{REF} and measuring the voltage across the combined C_{RH} and C_{REF} (V_{OUT}), the value of C_{RH} can be determined.

$$C_{RH} = C_{REF} (V_{REF} / V_{OUT} - 1) \tag{2}$$

However, deviations from an ideal system do exist and they introduce measurement errors. One such error source is Charge Injection from the switch. Analog Switches

introduce an undesirable injection of electrical charge into the circuit when the switch changes state. Charge Injection values in excess of 1pC are typical for monolithic switches and can alone result in an error equivalent to 2% RH.

Although this error could theoretically be removed through calibration, it has both temperature and supply voltage dependencies which make this impractical.

Charge based approaches also typically require a very high circuit impedance or the charge leakage will result in significant measurement errors. Even circuit impedances as high as 5GΩ can easily result in an equivalent error of greater than 0.5% RH. In high temperature and high humidity environments, such impedance levels are difficult to ensure - particularly over the entire operating life of a product.

Variations on this general approach were designed and evaluated as part of this project. These circuits were able to remove the net DC voltage from the sensor as well as minimize some of the above noted sources of error, however, they were unable to meet all of the System Requirements.

3.3. Bridge Approach

The use of an AC Bridge has long been used for measuring capacitance in a laboratory environment. As part of this project, the suitability of such an approach was explored for use in low energy industrial applications.
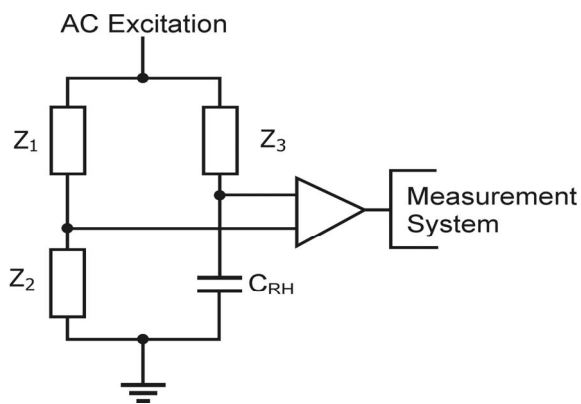

Figure 4 – Bridge Measurement Method

The approach which was evaluated was an unbalanced AC driven topology. The amount of unbalance is measured and is proportional to the capacitance of the RH sensor.

Using a typical RH Sensor, a signal of 100mV representing 0 to 100% RH from an unbalanced bridge was found to be practical. During development, the challenges associated with accurately measuring this signal level over a wide temperature range quickly became apparent. A variety of classic approaches were tried - using various combinations of precision rectifier circuits and instrumentation amplifiers. Available devices did not provide the needed combination

of speed, power and drift characteristics to make this approach suitable.

A method to accurately measure the bridge imbalance utilizing synchronous techniques was then developed from first principles. This approach utilizes a crystal oscillator (relatively low power and very stable over temperature) to both drive (excite) the bridge and perform a voltage subtraction between the bridge legs. Only low frequency (compared to the bridge excitation frequency) analog gain was required using this method and this was achievable over a wide operating range using standard devices.

By utilizing the same voltage source for both bridge excitation and the A/D (Analog to Digital Converter) reference input, ratiometric operation was achieved.

An oscillator frequency was chosen that would ensure adequately low energy consumption (400μJ per measurement), yet lower the impedance of critical nodes in the circuit. A leakage resistance as low as 500MΩ has been shown to introduce an equivalent error of just 0.1% RH.

The performance of the bridge (measuring the value of a fixed capacitor over a wide temperature) is shown below:
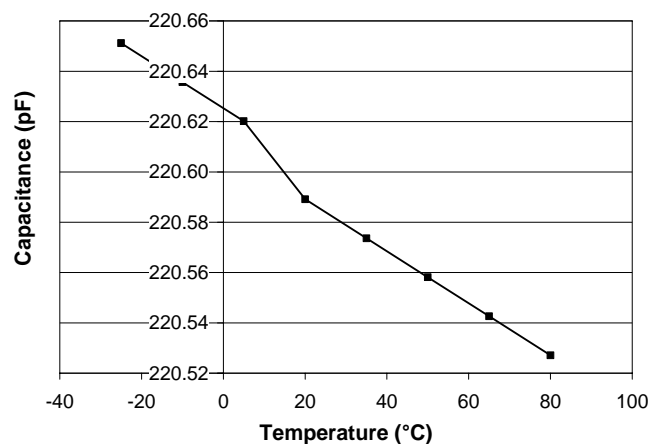

Figure 5 – Bridge Performance

This performance represents a capacitance measuring error of approximately 5.4 ppm/°C and produces an equivalent error of 0.25% RH over the range of -20° to 80°C.

Additionally, the AC excitation source has a controllable (digital) duty cycle and this allows adjustment at the time of manufacture to ensure that there is no net DC Voltage across the sensor.

4. CALIBRATION

As an OEM, the goal is to provide an accurate device calibration with a minimum number of calibration points.

When the system (with an RH Sensor installed) was profiled over a wide range of temperature and RH, the following was obtained:
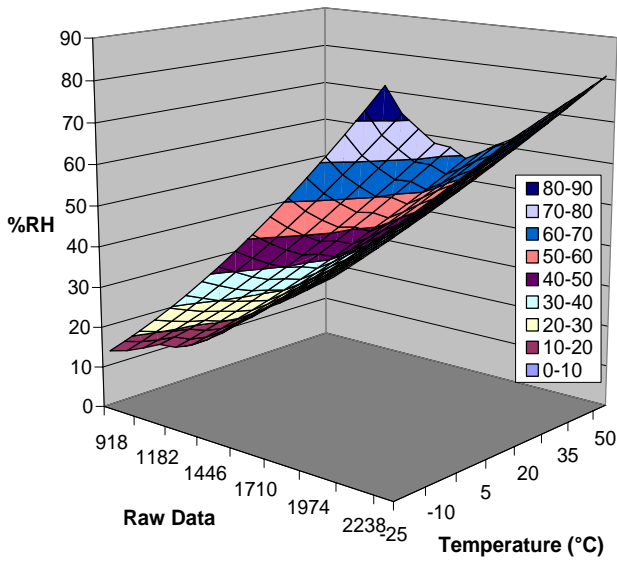
Figure 6 – Profile Dataset

In many traditional measurement systems, a best fit is performed over one particular calibration range (such as 25°C), but this may not provide an ideal fit for other ranges and overall measurement performance could be compromised. To maximize the overall system accuracy available from this electronic measuring system, other approaches were considered.

A number of units were profiled over a wide range of temperature and RH values. It was found that if the gain and offset were adjusted for each unit in both 'directions' of the surface (adjusted along RH at a fixed temperature and along temperature at a fixed RH) a good surface fit could be obtained. Five calibration points (three RH points at one temperature, and two temperature points at a fixed RH value) were found to provide a good compromise between measurement performance and calibration time.

A data set from the fitted surface is then expanded into an array of 256 tables covering the entire operating temperature range and is unique to each individual unit. This data is loaded into the unit's memory at the time of initial calibration.
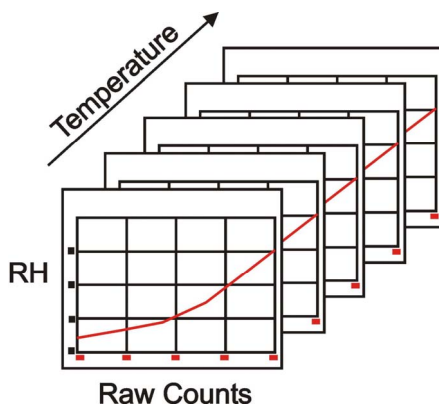

Figure 7 – Calibration Data Array

To obtain a measurement, the system first measures the temperature and uses this as an index into the array of tables. The system then measures the capacitance of the RH Sensor (Raw A/D Counts) and uses the selected table to convert from raw counts to RH. As this conversion is nearly linear at a given temperature, simple interpolation of table entries provides a good level of accuracy.

Such a large array allows specific calibration point(s) to be performed over one range without affecting calibration point(s) in another range and allows accurate wide-range calibrations to be performed. For example, a calibration performed at 15°C will not interfere with data obtained at 30°C as may occur with a traditional 'best overall fit' system.

5. CONCLUSION

During the development of Veriteq's new Humidity Data Logger, a number of measurement circuits were evaluated. An Unbalanced AC Bridge approach was adapted for low power/energy operation and was shown to provide good measurement performance over a wide operating range. A calibration method utilizing a large memory array was developed to maximize system performance.
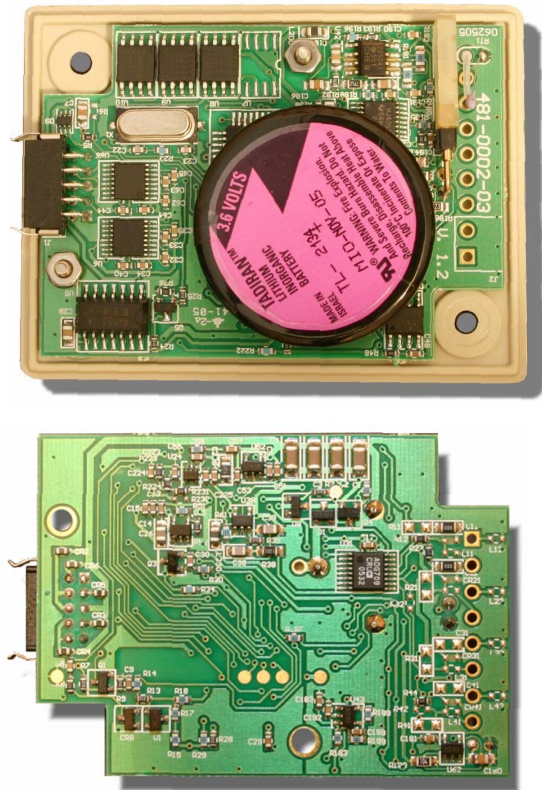

Figure 8 – Photo of Completed System

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