This is the title of a thesis submitted to Iowa State University

Note that only the first letter of the first word and proper names are capitalized

by

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DEDICATION

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ACKNOWLEDGEMENTS

1. Daji
2. Simon
3. Sebastian
4. Toby
5. Cat

ABSTRACT

This is the text of my abstract that is part of the thesis itself. The abstract describes the work in general and the heading and style match the rest of the document.

CHAPTER 1. OVERVIEW

The ever increasing availability of smaller, cheaper, and more power efficient electronic devices mixed with a new type of strain skin sensor makes possible new methods of infrastructure health monitoring of steel beams in bridges. This new system of custom skins sensors and controlling electronics can assist in the detection of fatigue cracks forming on bridges and other steel infrastructure.

1.1 Introduction

Iowa State University's Civil, Construction, and Environmental Engineering department has developed a new type of strain skin sensor. To enable the use of this new type of strain sensor requires a new high sensitivity data acquisition and logging system. This system must be small, energy efficient, and capable of measuring small changes in capacitance in a reasonably short amount of time. This data acquisition and logging circuitry will ultimately be networked by a wireless sensor network in order to detect fatigue cracks forming on a bridge and assessing the overall health of the bridge during phase two of the project.

1.1.1 Capacitive Skin Sensor

This project revolves around a capacitive strain skin sensor develop by the Iowa State University department of Civil, Construction, and Environmental Engineering under the direction of Dr. Simon Laflamme.

1.1.1.1 Parts of the hypothesis

Here one particular part of the hypothesis that is currently being explained is examined and particular elements of that part are given careful scrutiny.

1.1.2 Capacitive Measurement

Here one particular hypothesis is explained in depth and is examined in the light of current literature.

1.1.2.1 Parts of the second hypothesis

Here one particular part of the hypothesis that is currently being explained is examined and particular elements of that part are given careful scrutiny.

1.1.3 Data Acquisition

1.2 Criteria Review

Here certain criteria are explained thus eventually leading to a foregone conclusion.

CHAPTER 2. METHODS AND PROCEDURES

2.1 Design Requirements

This project was completed in collaboration with a parallel project to develop a strain sensor by the Department of Civil, Construction, and Environment Engineering at Iowa State University. The design requirements were set by that project and are given here.

2.1.1 Measured Parameter

The purpose of this project is to measure strain using the capacitive strain sensor designed in a parallel project. The project requirement is to measure strain at a resolution of one micro-strain over a range of minus five-hundred to plus five-hundred micro-strain from the unstrained position. The data acquisition system must be self calibrating and able to quickly recalibrate in the field.

2.1.2 Output Format

The output from the data acquisition circuit must be in a format that can be accurately measured by a data logging circuit such as an Intel iMote2. In addition a custom logging circuit was designed which interfaces with the data acquisition circuit and reports the results to a computer over a USB connection.

2.1.3 Power Requirements

In a future phase of this project the sensors and data acquisition system will be deployed onto remote bridges in a sensor network scheme. After deployment the entire system will need to run using energy harvested from the surrounding environment. Due to this restriction care must be taken throughout the design to ensure the minimum energy is required to measure the strain.

2.2 Capacitive Skin Sensor

The strain sensor used in this project is a soft elastomeric capacitor (SEC) developed by the Department of Civil, Construction, and Environmental Engineering at Iowa State University. The SEC is composed of a nanocomposite mix of poly-styrene-co-ethylene-co-butylene-co-styrene (SEBS) (Dryfelx 500120) doped with rutile TiO_2 (Sachtleben R 320 D) serving as a dielectric for the capacitor**?**).

2.2.1 Capacitive properties

The strain to capacitance properties were shown by Dr. Laflamme et al. to be the form shown in Equation 2.1. The parameter C_0 is the nominal capacitance of the sensor and is estimated to be in the range of 500pF. The value of the gain factor λ is dependent on the geometry of the sensor; it is 2 for the capacitive skin sensors used in this study. The value of ϵ_s is the strain seen by the sensor and ΔC is the change in the capacitance of the sensor due to that strain. This can be rewritten in the form of Equation 2.2

$$\frac{\Delta C}{C_0} = \lambda \epsilon_s \tag{2.1}$$

$$\Delta C = \lambda C_0 \epsilon_s \tag{2.2}$$

The overall capacitance of the strain sensor is the nominal capacitance plus the capacitance due to an applied strain. This capacitance C_{sens} is shown in Equation 2.3. The capacitance due to strain is much smaller than the nominal capacitance; it is on the order of femtofarads for an applied strain of one micro strain. The typical values for the parameters of a capacitive skin sensor are shown in Table 2.1.

$$C_{sens} = C_0 + \Delta C = C_0 + \lambda C_0 \epsilon_s = C_0(1 + \lambda \epsilon_s) \tag{2.3}$$

Parameter	Typical Value
C_0	500pF
λ	2

Table 2.1 Typical capacitive strain gauge parameters

2.3 Capacitive Measurement Circuit

2.3.1 Challenges

The capacitance change that needed to be measured was on the order of $1fF$ on a capacitor with a nominal capacitance of $500pF$. This is a change on the order of one part per 500,000. Using traditional methods of capacitance measurement is unable to measure at this required sensitivity.

2.3.1.1 Traditional Methods of Capacitance Measurement

There are many traditional methods for measuring capacitance which were explored as possible solutions and determined to be ineffective for solving this problem. To accurately measure these small changes in capacitance a circuit with a high sensitivity to capacitance change is required. Sensitivity is the measure of how much a output parameter changes due to a change of an input parameter. In general the equation for sensitivity is given in Equation 2.4 where x is the input parameter and y is the output parameter.

$$S = \lim_{\Delta x \to 0} \frac{\Delta y / y}{\Delta x / x} = \frac{x}{y} \frac{\partial y}{\partial x} \tag{2.4}$$

In the context of measuring the capacitance of the stain sensor where the base capacitance is C_0 and the change in capacitance is ΔC define the output parameter as the frequency at capacitance C is define as $f(C)$, then the sensitivity equation becomes the form shown in Equation 2.5 or Equation 2.6.

$$S = \lim_{\Delta C \to 0} \frac{\left(f\left(C_0 + \Delta C\right) - f\left(C_0\right)\right) C_0}{f(C_0) \Delta C} \tag{2.5}$$

$$= \frac{C_0}{f(C_0)} \left[\frac{\partial f(C)}{\partial C} \right]_{C=C_0} \tag{2.6}$$

LCR oscillator circuits are circuits that oscillate at a frequency proportional to the capacitance of the sensor and fixed inductor value. The frequency of these circuits is proportional to $1/\sqrt{C}$. Given the sensitivity equation in Equation 2.6 the sensitivity of a LCR oscillator circuit can be calculated in Equation 2.8.

$$
\begin{aligned}
f &:= \frac{\alpha}{\sqrt{(C)}} && (2.7)\\
S &= \frac{C_0\sqrt{C_0}}{\alpha}\left[\frac{-\alpha}{2C\sqrt{C}}\right]_{C=C_0} = -1/2 && (2.8)
\end{aligned}
$$

Therefore this circuit has a very small sensitivity to changes in capacitance is not a valid solution for the problem.

Charge time measurement is a method of measuring the capacitance of a circuit by measuring the time for that circuit to charge to a set amount. This method involves charging the capacitor with a constant current source and measuring the time to charge to one time constant. The voltage through a capacitor which is charging by a constant current source I is $V(t) = \frac{I}{C}t$. Therefore if the measured parameter is the time t to charge to a given voltage V the time to charge is given in Equation 2.9, then from Equation 2.4 the sensitivity is given in Equation 2.10

$$t = \frac{C}{I}V \tag{2.9}$$

$$S = \frac{C_0}{C_0V/I}\frac{V}{I} = 1 \tag{2.10}$$

A relaxation oscillator is a simple type of oscillator which produces a square wave at a frequency proportional to the capacitor value. The circuit for a basic relaxation oscillator is shown in Figure 2.1. This circuit oscillates at a frequency f show in Equation 2.11.

$$f = \frac{1}{2\ln(3)RC} \tag{2.11}$$

Therefor the sensitivity can be calculated using Equation 2.6 and is shown in Equation 2.12.

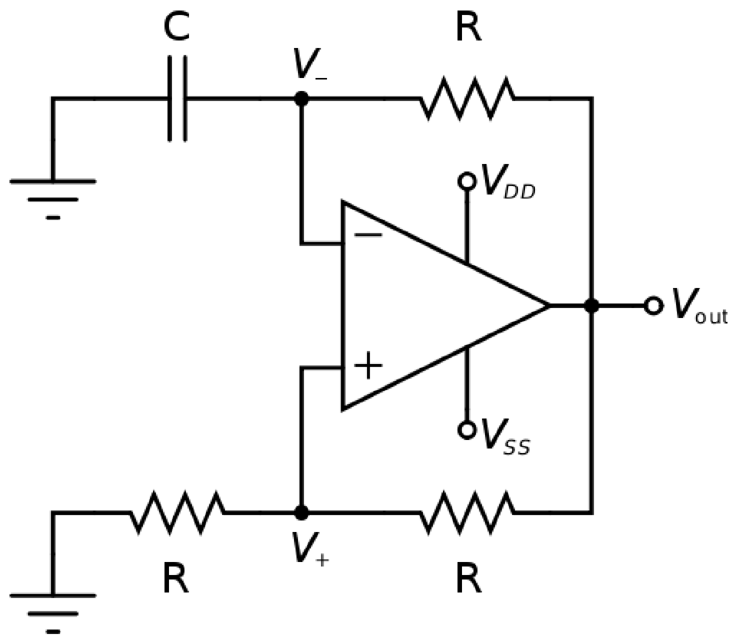

Figure 2.1 Simple relaxation oscillator circuit.

$$S = \frac{C_0}{1/(2\ln(3)RC_0)} \frac{-1}{2\ln(3)RC_0^2} = -1 \tag{2.12}$$

2.3.2 Design

None of the traditional methods of capacitance measurements explored are capable of achieving the sensitivity required to accurately measure the small changes of capacitance produced by the strain sensor. For example, if the relaxation oscillator was used to measure a $1fF$ change in a $500pF$ capacitor assuming $R = 910\Omega$ yields the frequencies shown in Equations 2.13 and 2.14.

$$f_{\text{unstrained}} = \frac{1}{1820\Omega\ln(3)(500\text{pF})} = 1.0002628864\text{MHz} \tag{2.13}$$

$$f_{\text{strained}} = \frac{1}{1820\Omega\ln(3)(500\text{pF} + 1\text{fF})} = 1.00026088588\text{MHz} \tag{2.14}$$

This corresponds to a change in frequency of approximately 2Hz; an effective change of two parts per million. Clearly it is impractical to measure this value in a real system. A system had to be designed to greatly increase the sensitivity of the data acquisition circuit to the expected small changes in capacitance.

The problem with the other capacitance measurement techniques is the relatively large nominal capacitance of the skin sensor to its small change in capacitance due to an applied strain. The approximate expected nominal capacitance is 500pF with a change of capacitance on the order of 1fF; this is a change of one part per five-hundred thousand. The overall range of capacitance change expected is relatively small in comparison to the nominal capacitance; in the case of a sensor measuring 500 micro-strain can expect a capacitance change of 500fF or 0.5pF. Define the variable C_{max} as this maximum expected capacitance change. The solution is therefore to cancel out the nominal capacitance such that the only capacitance contributing to the measured frequency is the capacitance due to strain.

The equivalent capacitance of capacitors in parallel is the sum of the capacitance of each capacitor. Therefore connecting the strain sensor in parallel with a capacitor of C shown in Equation 2.15 will yield an equivalent capacitance of C_1. By designing the system such that $C_1 = C_{max} + \epsilon$ the capacitance over the range of ± 500 micro-strain will be $\epsilon \leq C_{eq} \leq C_{max} + \epsilon$. This capacitance C_{eq} can be used as an input to one of the traditional capacitance measurement techniques.

$$C = C_1 - C_0 \tag{2.15}$$

The relaxation oscillator circuit was chosen due to its higher sensitivity, relatively cheaper cost, and lower energy requirements compared to the other measurement techniques.

2.3.2.1 Negative capacitive circuit

The basic negative capacitor circuit used for this project is shown in Figure 2.2. This is a well established and common configuration used to create negative impedance circuits. It has many useful features including the ease of setting the impedance by changing the value of a single potentiometer.

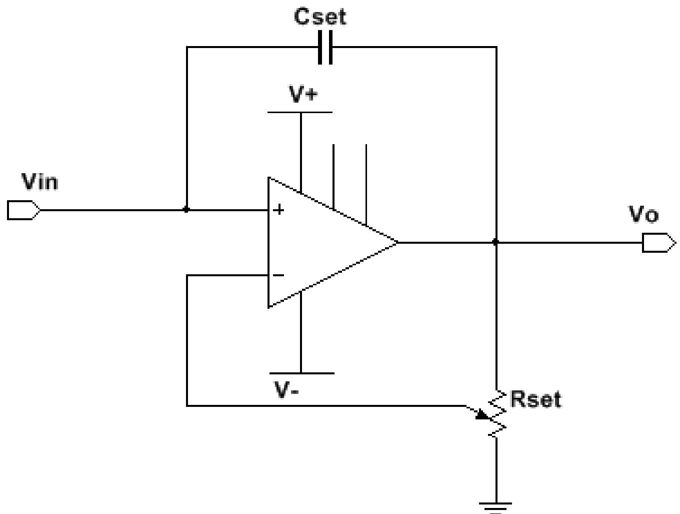

Figure 2.2 Negative capacitance circuit schematic

The negative feedback circuit forms a basic voltage divider circuit between the Op-Amp output and ground. Therefore the Op-Amp output voltage V_o is given in Equation 2.16 where $x \in [0, 1]$ is the position of the potentiometer.

$$V_o = \frac{1}{x} V_{in} \geq V_{in} \tag{2.16}$$

The positive feedback circuit has an impedance $Z_{set} = \frac{1}{sC_{set}}$ where s is the Laplace operator. The input current I_{in} can be calculated using Equation 2.17. This represents the current sunk or sourced at the input to the negative impedance circuit.

$$I_{in} = \frac{V_{in} - V_o}{Z_{set}} \tag{2.17}$$

The circuit impedance of the negative impedance circuit is given by Ohms law as $V_{in} = ZI_{in}$. Using the calculated V_o from the negative feedback circuit and using that into the positive feedback circuit calculation the impedance of the circuit is calculated in Equation 2.20. Using the fact that $Z = \frac{1}{sC_{set}}$ the equivalent capacitance of the circuit is shown in Equation 2.21.

$$I_{in} = \frac{V_{in} - \frac{1}{x}V_{in}}{Z_{set}} \tag{2.18}$$

$$= \frac{\frac{x-1}{x}V_{in}}{Z_{set}} \tag{2.19}$$

$$\Downarrow$$

$$Z_{eq} = \frac{V_{in}}{I_{in}} = \frac{x}{x-1}Z_{set} \leq 0 \tag{2.20}$$

$$Z_{eq} = \frac{1}{sC_{eq}} = \frac{x}{sC_{set}(x-2)} \Rightarrow C_{eq} = \frac{x-1}{x}C_{set} \tag{2.21}$$

In the implementation the potentiometer is digitally controlled to allow real time calibration of the system. The potentiometer chosen was the CAT5259 manufactured by ON Semiconductors. This potentiometer divides the range linearly into eight bits of resolution. Therefore the x in Equation 2.21 must be chosen such that $x \in \{\frac{k}{2^8} : k \in \mathbb{N}, k < 2^8\}$. Therefore the equivalent capacitance of the circuit in terms of the integer value $k \in [0, 256)$ is shown in Equation 2.23.

$$C_{eq} = \frac{x-1}{x}C_{set} \tag{2.22}$$

$$\frac{C_{eq}}{C_{set}} = \frac{k-2^8}{k} \tag{2.23}$$

This capacitance is plotted over the range of $k \in [23, 255]$ and $k \in [85, 255]$ in Figures 2.3 and 2.4 respectively. By choosing $C_{set} \approx C_0$ of the sensor the negative capacitor circuit can stay within the nearly linear region shown in Figure 2.4.

2.3.2.2 Relaxation oscillator

The same relaxation circuit shown in Figure 2.1 is used to convert the change in capacitance into a change in frequency with the one key change: the capacitor is the parallel combination of the sensor C_{sens} and the negative capacitance C_1. The equivalent capacitance of this parallel combination is the sum of both capacitors, $C = C_{sens} + C_1$ where C_1 is the equivalent capacitance of the negative capacitance circuit calculated in Equation 2.22.

Assuming all resistors R in the relaxation oscillator are equal the frequency output of the oscillator is repeated in Equation 2.24. Using the new value for the capacitance input of the

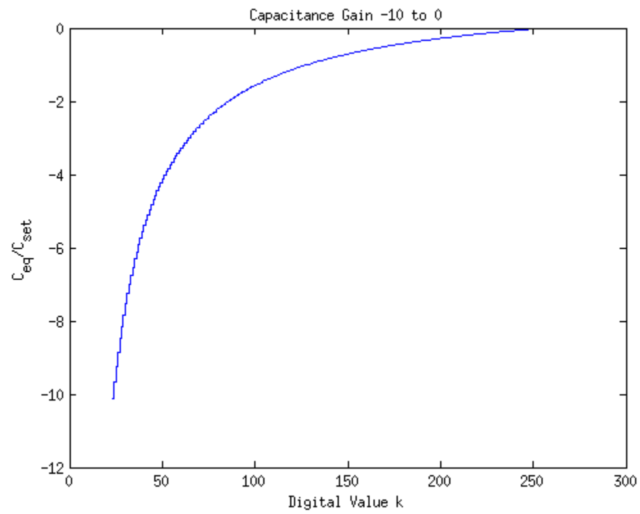

Figure 2.3 Negative capacitance gain from -10 to 0

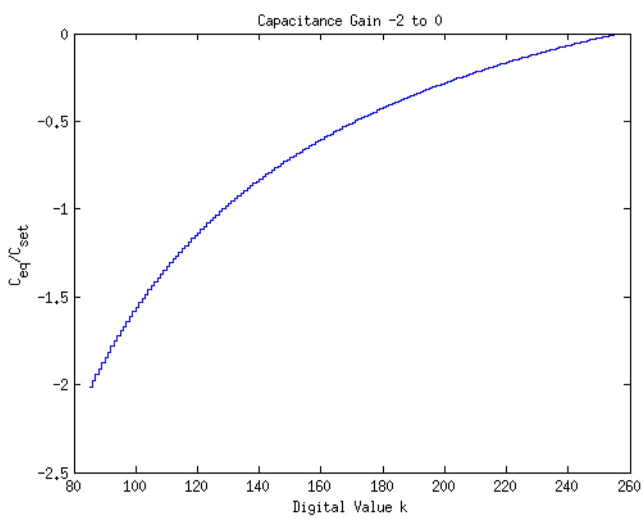

Figure 2.4 Negative capacitance gain from -2 to 0

oscillator yields a new frequency equation shown in Equation 2.25. Combining the definition of C_1 from Equation 2.22 the equation shown in Equation 2.26 can be obtained for the frequency output in terms of the C_{sens} and digital value k.

$$f(C) = \frac{1}{2\ln(3)RC} \tag{2.24}$$

$$f(C_{sens}, C_1) = \frac{1}{2\ln(3)R(C_{sens} + C_1)} \tag{2.25}$$

$$f(C_{sens}, k) = \frac{1}{2\ln(3)R(C_{sens} + \frac{k-256}{k}C_{set})} \tag{2.26}$$

From the model of the capacitive skin sensor, the value of C_{sens} has two components: the first component is the unstrained base capacitance and the second is the change in capacitance due to strain. Therefore by writing C_{sens} in the form of Equation 2.27 the frequency equation in Equation 2.26 becomes Equation 2.28.

$$C_{sens} = C_0 + \Delta C \tag{2.27}$$

$$f(\Delta C, k) = \frac{1}{2\ln(3)R(C_0 + \frac{k-256}{k}C_{set} + \Delta C)} \tag{2.28}$$

The sensitivity of this new capacitive measurement system can be calculated using the definition of sensitivity given in Equation 2.6 and the frequency equation given in Equation 2.26. First the derivative of the frequency with respect to the capacitance of the sensor is calculated in Equation 2.30. Form this the sensitivity can be calculated in Equation 2.33. Including the definition of C_{sens} given in Equation 2.27 gives the resulting sensitivity in Equation 2.35.

$$\frac{\partial f(C_{sens})}{\partial C_{sens}} = \frac{\partial}{\partial C_{sens}}\left[\frac{1}{2\ln(3)R(C_{sens}+\frac{k-256}{k}C_{set})}\right] \tag{2.29}$$

$$= \frac{1}{2\ln(3)R(C_{sens}+\frac{k-256}{k}C_{set})^2} \tag{2.30}$$

$$S = \frac{C_{sens}}{f(C_{sens})}\frac{\partial f(C_{sens})}{\partial C_{sens}} \tag{2.31}$$

$$= \frac{C_{sens}(2\ln(3)R(C_sens+\frac{k-256}{k}C_{set})}{2\ln(3)R(C_{sens}+\frac{k-256}{k}C_{set})^2} \tag{2.32}$$

$$= \frac{C_{sens}}{C_{sens}+\frac{k-256}{k}C_{set}} \tag{2.33}$$

$$= \frac{C_0+\Delta C}{C_0+\frac{k-256}{k}C_{set}+\Delta C} \tag{2.34}$$

$$= \frac{C_0}{C_0+\frac{k-256}{k}C_{set}+\Delta C}+\frac{\Delta C}{C_0+\frac{k-256}{k}C_{set}+\Delta C} \tag{2.35}$$

Define a new variable α as given in Equation 2.36. By choosing k and C_{set} such that α is small the sensitivity becomes very large reaching a theoretical maximum of $C_0/\Delta C+1$ when $\alpha = 0$.

$$\alpha := C_0+\frac{k-256}{k}C_{set} \tag{2.36}$$

$$S = \frac{C_0}{\alpha+\Delta C}+\frac{\Delta C}{\alpha+\Delta C} \tag{2.37}$$

Parameter selection is based on the design requirements. The design requirements specify the need to measure $1\mu\epsilon$ resolution over a range of $\pm 500\mu\epsilon$ from unstrained. Define ΔC_ϵ to be the change in capacitance of the sensor due to a $1\mu\epsilon$ strain, then the maximum and minimum values of ΔC are $\Delta C_{max} = 500\Delta C_\epsilon$ and $\Delta C_{min} = -500\Delta C_\epsilon$ respectively.

To achieve maximum sensitivity α must be chosen as small as possible; however, if the denominator of Equation 2.28 becomes negative the system poles of the system will move into the right half plan causing the circuit to become unstable. Therefore the constrain equation shown in Equation 2.38 must be true for all ΔC in the range.

$$C_0 + \frac{k-256}{k} C_{set} + \Delta C = \alpha + \Delta C \quad > \quad 0, \quad \forall \quad \Delta C \in [\Delta C_{min}, \Delta C_{max}] \tag{2.38}$$

$$\alpha \quad > \quad -C_{min} \tag{2.39}$$

Using this value of α the values of C_{set} and k can be set. Choose $C_{set} \approx 2C_0$ to force k into a sensitive and approximately linear region in Figure 2.4. Since the nominal capacitance of the capacitive skin sensors is approximately 500pF choose C_{set} =1nF. With this value k can be calculated to be 171 giving making $\alpha = 2.9 \times 10^{-12}$. Plugging these numbers into Equation 2.37 gives a theoretical sensitivity of 3.4×10^{11}. It should be noted that this theoretical value could never be achieved in a real system; however, this shows the high sensitivity potential of this circuit.

The capacitive sensor is characterized for oscillation frequencies under one kilohertz.

2.3.3 Output

The output form the data acquisition circuit is a square wave which has a frequency dependent on the strain of the sensor. Due to limitations on the sensor due to its physical properties, the oscillation frequency must be kept below one kilohertz.

2.4 Data Acquisition Circuit

2.4.1 Measured parameter

2.4.1.1 Measurement method

2.4.2 Calibration

2.4.2.1 Self calibration

2.4.3 Communication protocol

2.5 Testing Software

2.5.1 Computer companion program

CHAPTER 3. RESULTS

CHAPTER 4. SUMMARY AND DISCUSSION

APPENDIX A. ADDITIONAL MATERIAL

APPENDIX B. STATISTICAL RESULTS