RFRD Phase II

TO DESIGN A RADIO FREQUENCY READOUT DEVICE TO USE IN A BOLT ANCHOR SURVEYING APPLICATION.

Team 11
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1 Introduction

1.1 ACKNOWLEDGEMENT

We would like to acknowledge the support from our advisors Dr. Daji Qiao and Dr. Nathan Neihart. We would also like to thank Scott Melvin and Chengrui Yang for our task assistance throughout the semester.

1.2 PROBLEM AND PROJECT STATEMENT

The purpose of this project is to reduce the time it takes to check each nut for tightness on bolts of large lamp post structures. Each nut currently, must be manually checked for tightness with large tools to ensure that the structure is sound.

To address this problem, this project will use a Radio Frequency Readout Device (RFRD) to read if each nut is secured tightly or if it needs to be properly torqued. This RFRD will be usable in a vehicle at a distance to reduce the time it is needed to check each structure. The RFRD reader will be designed to power a RFRD tag, which will read the capacitance value of washers between a bolt and nut. The capacitance value will be transmitted back to the RFRD reader and tell the user if the nut is tight or loose.

1.3 OPERATIONAL ENVIRONMENT

The RFRD tag will be attached to a metal lamppost structure and will be subject to weather conditions. The RFRD reader will be used in a vehicle or dry weather conditions.

1.4 INTENDED USERS AND USES

The RFRD reader and tag are intended to be used by civil engineers and construction workers on lamp posts and other larger structures that require inspections to the structures integrity and tightness of its fasteners.

1.5 ASSUMPTIONS AND LIMITATIONS

Assumptions for prototype:

The reader will supply ~ 0.45 mW of power wirelessly to the tag at a distance of ~ 1 meter. We were able to assume this value based on IEEE article, "A Compact Fractal Loop Rectenna for RF Energy Harvesting".

Limitations for prototype:

The RF tag must operate on less than 0.45 mW of wirelessly harvested power.

1.6 EXPECTED END PRODUCT AND DELIVERABLES

The expected deliverables are as follows: a printed circuit board that will be complete with a capacitance measuring circuit, a low power microcontroller, an inverted-F antenna, and a rectifier.

We are expected to be able to demonstrate wireless functionality of our design at any distance.

Our delivery dates will be expected by finals week in May of 2018.

2. Specifications and Analysis

2.1 PROPOSED DESIGN

The goal of this project is to design a radio frequency readout device (RFRD) to use in an anchor bolt surveying application.

We have three major components of our design:

1) Capacitance sensing circuit

2) Rx/Tx module including antenna and power harvesting circuitry

3) RFRD reader

A simple block diagram for our design is as follows:

Figure 1: RFRD Block Diagram

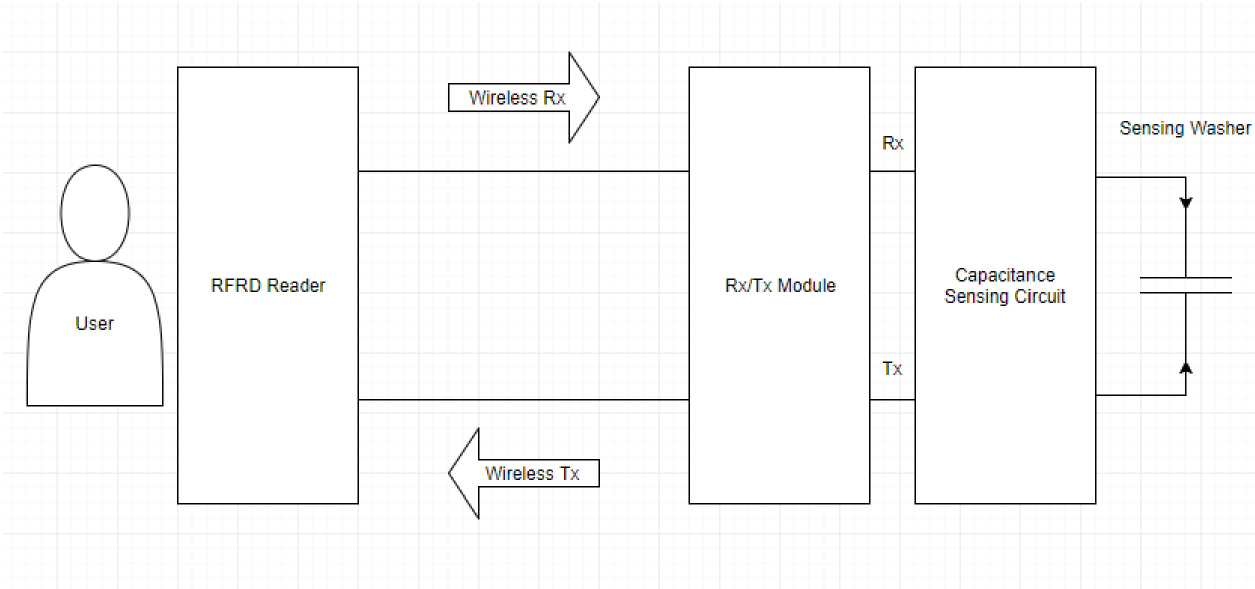
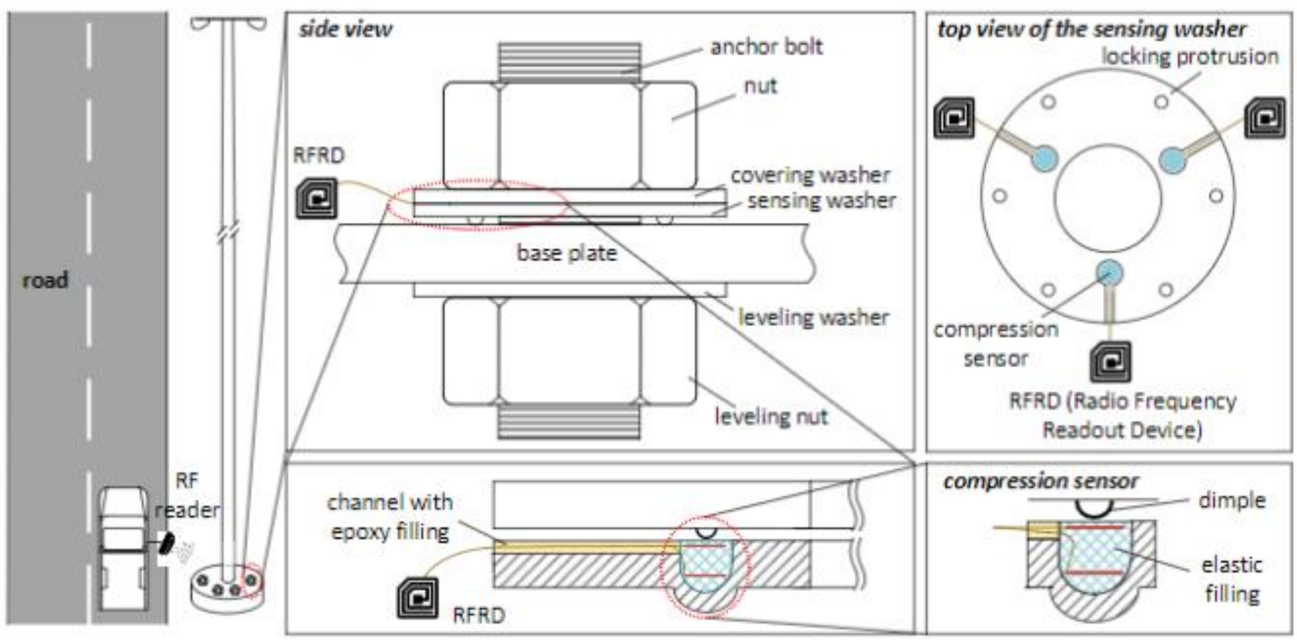


Figure 2: Mechanical Design



We tested the washer design by soldering two wires, one on the covering and another on the sensing washers. We then measured the capacitance of the system using an LCR meter. We concluded as follows:

Test 1: Resting washers: 20 pF

Test 2: No contacting washers: 2 pF

Test 3: Pressured washers: 30 – 40 pF

This concludes that our measuring range for our relaxation oscillator will be from 20 pF to 50 pF.

We also performed additional tests using the LCR meter at multiple measuring frequencies. We noted the following measurements:

Figure 3: LCR Measurements

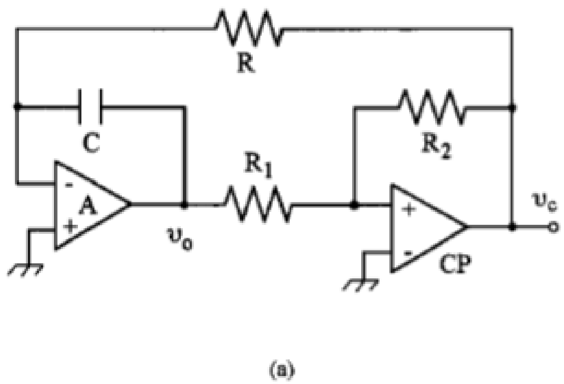
	A	B	C	D	E	F	G	H	I	J	K	L	M	N
1	Sitting Normally								Pressing					
2														
3	f = 20Hz								f = 20Hz					
4		Cp =	27 to 28pF		Cs =	27 to 28pF				Cp =	35.8pF		Cs =	37pF
5		Rp =	3 to 4 GΩ		Rs =	19 to 25MΩ				Rp =	1.2GΩ		Rs =	29 to 34MΩ
6		Q =	10 to 15		Q =	10 to 15				Q =	6 to 8		Q =	5 to 7
7														
8	f = 10kHZ								f = 10kHZ					
9		Cp =	25.4pF		Cs =	25.4pF				Cp =	31.3pF		Cs =	32.2pF
10		Rp =	34.7MΩ		Rs =	11.2kΩ				Rp =	18.3MΩ		Rs =	14.6kΩ
11		Q =	55.8		Q =	55.5				Q =	38.5		Q =	37
12														
13	f = 300kHz								f = 300kHz					
14		Cp =	23.9pF		Cs =	24.49pF				Cp =	29pF		Cs =	28.7pF
15		Rp =	2.5 to 5MΩ		Rs =	-215 to 215Ω				Rp =	1.3MΩ		Rs =	230 to 235Ω
16		Q =	Not Consistent		Q =	Not Consistent				Q =	60 to 64		Q =	79 to 81

This concludes that the quality factor (Q) for our sensing washers are the most consistent while measuring at 10 kHz. We will tune our relaxation oscillator to this range while measuring the capacitance of the sensing washer.

Relaxation Oscillator Version 1:

We are designing a relaxation oscillator to measure from 20 – 50 pF with ~1% measuring error. We referenced a design in the published IEEE article, "Limitations of a Relaxation Oscillator in Capacitance Measurements" by Yili Liu, Song Chen, Masakatsu Nakayama, and Kenzo Watanabe.

Figure 4: Relaxation Oscillator Version 1



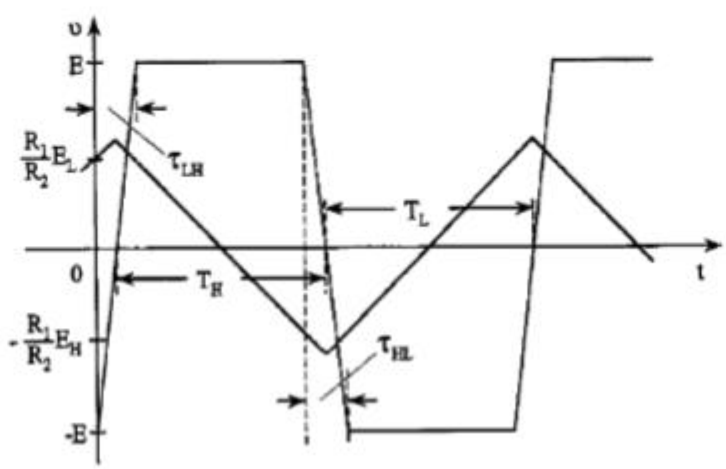
We can use relaxation oscillators to measure capacitance since they are designed to produce a pulse signal that changes the oscillation period linearly with capacitance measured in C (circuit above).

Figure 5: Oscillation Period Equation

The oscillation period T is thus

$$T = T_H + T_L = CR\frac{R_1}{R_2}\left(2+\gamma+\frac{1}{\gamma}\right). \qquad (6)$$

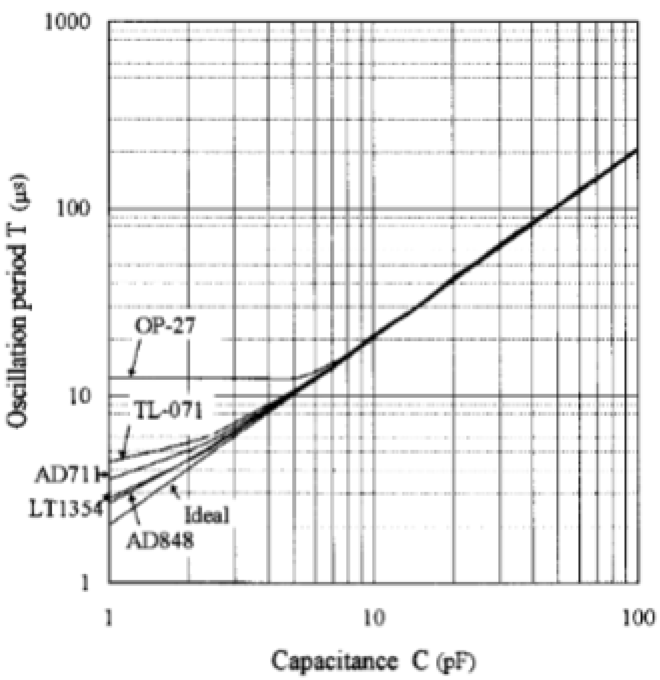
Figure 6: Relaxation Oscillator Proposed Output



Op Amps for Relaxation Oscillator:

For this application, we will need to use very low-power op amps. In the article, they tested five op amps to measure the percent error achieved with each op amp. The below op amps are not a very low-power application.

Figure 7: Percent Error for Tested Op Amps



In order to calculate our very low-power op amp criteria, we used the following equations from the above IEEE article.

Figure 8: Op Amp Equations

The derivation of (18) assumes

$$SR > \frac{E}{CR}. \qquad (19)$$

For the error to be less than ε%, an op-amp and a comparator with the following specifications are required:

$$A_o\omega_c > \frac{100}{\varepsilon CR}\left\{1 + \frac{1}{2\alpha}\left(1 + \frac{C_i}{C}\right)\right\} \qquad (20)$$

$$\tau < \frac{2\alpha\varepsilon CR}{100}. \qquad (21)$$

These derivations tell us our minimum slew rate, gain-bandwidth product, and time response delay our op amp needs to satisfy in order to produce an error less than e%.

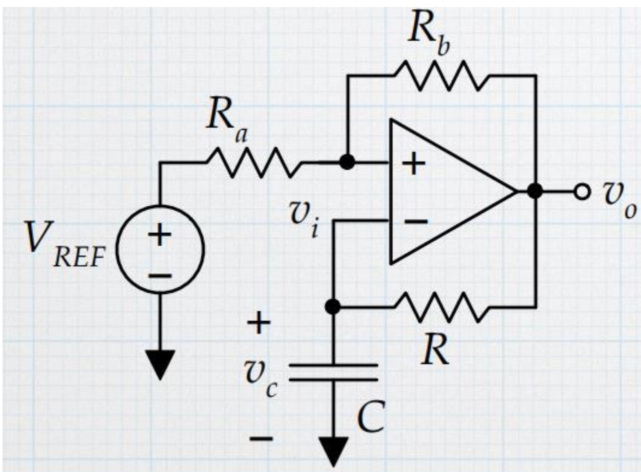
Version 1 Conclusion:

We were not able to demonstrate functionality of this design using SPICE. This led us to look further into simplifying our design.

Relaxation Oscillator Version 2:

This design is a simplified version of version 1. The functionality of this design is using a comparator circuit with a capacitor tied to the inverted input of the op amp. We were able to use derivations and figures from Dr. Gary Tuttle's EE 230 webpage.

Figure 9: Relaxation Oscillator Version 2

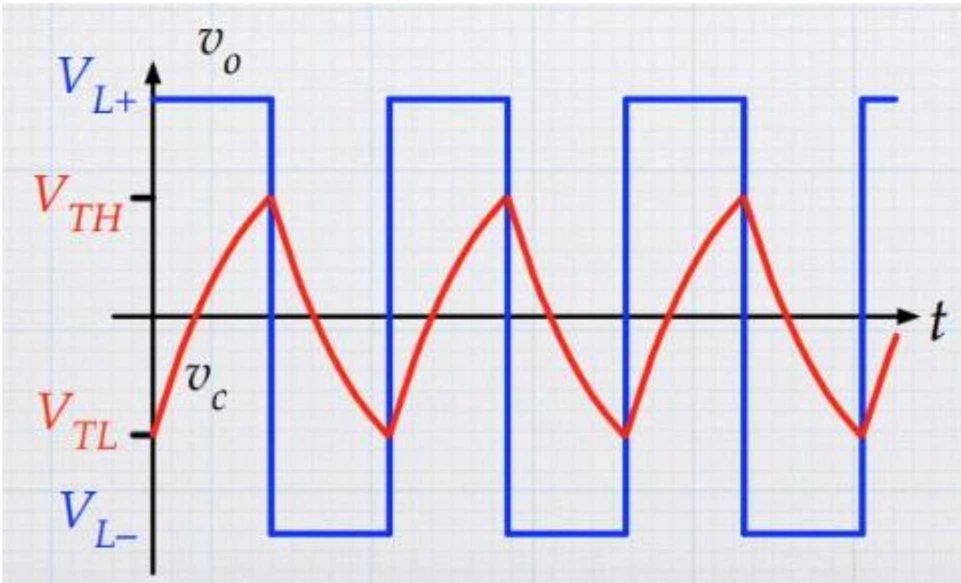


This relaxation oscillator will generate a PWM wave with a period as follows.

Figure 10: Relaxation Oscillator Version 2 Period Formula

$$\text{Period:} \quad T = T_H + T_L = RC \ln \left[\frac{(V_{S+} - V_{TL})(V_{S-} - V_{TH})}{(V_{S+} - V_{TH})(V_{S-} - V_{TL})} \right]$$

Figure 11: Relaxation Oscillator Version 2 Theoretical Output



Since this circuit uses a comparator, we decided to use the STMicroelectronics TS88 comparator IC. This chip is very low power and uses ~1.285 uW per our simulations below.

Conclusion:

This design will be our capacitance measuring circuit going forward. Our end goal is to fabricate the circuit on a printed circuit board with surface mount technology.

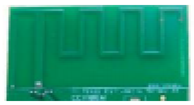
Capacitance measurement circuit collaborators: Bailey Akers and Colin Sunderman

Rx/Tx Module Design:

Antenna Design:

The design team is looking into designing an inverted-F antenna PCB to use for our application. We decided on the inverted-F antenna since the efficiency is the greatest at the tag area we are roughly projecting. Our antenna will be designed for the operation at 900 MHz.

Figure 12: Typical Efficiency for an Inverted-F Antenna from Texas Instruments Antenna Selection Guide



Design / Application Note	DN023
Frequency	868 / 915 / 920 MHz
Typical Efficiency	80%(SA)
Bandwidth @ VSWR 2:0	40 MHz
Dimensions (mm)	43 x 20

We have estimated an expected received power of ~0.45 mW at 1-meter distance from reader to tag. This estimation was given from the paper, "A Compact Fractal Loop Rectenna for RF Energy Harvesting". In the paper, they used a fractal loop antenna, while we will be using an inverted-F antenna.

Power Harvesting Design:

We plan on using a rectifier in series with the antenna.

RFRD Reader/Communication Protocol Design:

The communication between the tag and the reader will be one-way digital communications. A microcontroller will be utilized on the tag for reading and processing the signal received from the capacitance sensor. The microcontroller will send the information to the reader where it will be displayed to the user.

The microcontroller we will be using will be from ST's line of ultra-low power ARM based MCU's. These are ARM Cortex M0+ processors capable of running in the micro amp range. ST also has a very easy to use tool chain that will allow the software to be easily written or converted to run on other ST microcontrollers.

The information being sent form the reader will be of very little complexity and length allowing us to use a very simple protocol. It will be comprised of a single digital string that contains the tag ID, the status of the washer including if the pressure on the washer has changed, and a checksum to allow for the detection of any errors that might occur during communications.

For initial testing and prototyping we will be using a software-defined radio for the receiver. This is a type of radio were all the processing is done in software running on a computer and allows for greater flexibility of protocols. This will allow us to implement any protocol or communication system that we may need. There are many options for SDR's and we have not yet decided on an exact product.

2.2 DESIGN ANALYSIS

Capacitance Measuring:

We spent a lot of time trying to implement the first version of the relaxation oscillator. We have concluded on the second version of the oscillator and have demonstrated its functionality. We have concluded on using the STMicroelectronics TS88 comparator IC for our prototype which is well under the limitation of 0.45 mW power consumption.

Power Harvesting:

We have concluded that we expect to receive ~0.45 mW of power from the RFRD reader at ~1 meter distance. We have also concluded on the inverted-F antenna design. We will design our antenna similar to the DN023 application note from Texas Instruments.

3 Testing and Implementation

3.1 INTERFACE SPECIFICATIONS

We will need to be able to simulate our relaxation oscillator and inverted-F antenna designs using software. This will enable us to fix errors before manufacturing the PCB's.

3.2 HARDWARE AND SOFTWARE

Capacitance Measuring Circuit:

We will be working with OrCad Capture SPICE simulation in order to simulate our relaxation oscillator with STMicroelectronics op amps.

Antenna Group:

We will be using ADS software to simulate the DN023 inverted-F antenna to see what frequency it operates at.

Communication Group:

A USRP-2920 is being used to as the receiver. GNU Radio will be used to decode the signal received from the tag.

3.3 PROCESS

Capacitance Measuring Circuit:

We tested our relaxation oscillator by calculating the period of oscillation for our chosen components, then measuring the period of oscillation that was simulated with OrCad Capture.

We then tuned our resistance values to obtain an accurate reading of capacitance in our simulation.

Lastly, we updated the reference voltages for the comparator IC in order for the output to be in the positive voltage region of operation.

Inverted-F Antenna:

We are simulating the DN023 inverted-F antenna design using Momentum in order to obtain the operation frequency of the antenna.

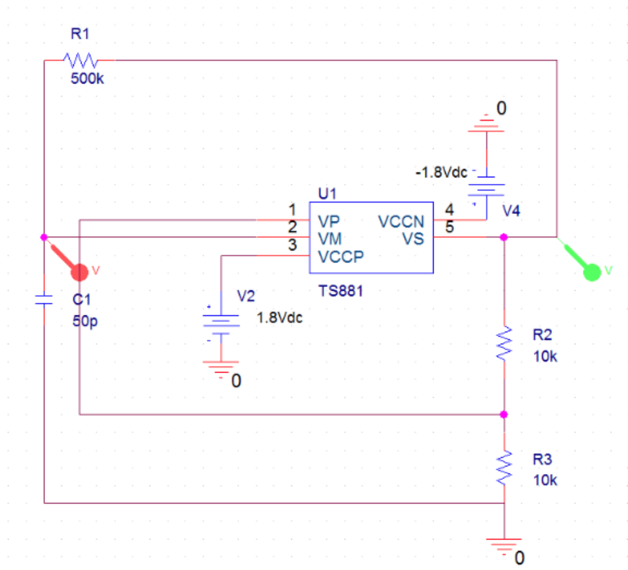
Microcontroller and Communications:

Simulation will be performed next semester once the software defined radio is obtained.

3.4 RESULTS

Capacitance Measuring Relaxation Oscillator Version 2 Simulations:

Figure 13: Relaxation Oscillator Version 2 SPICE

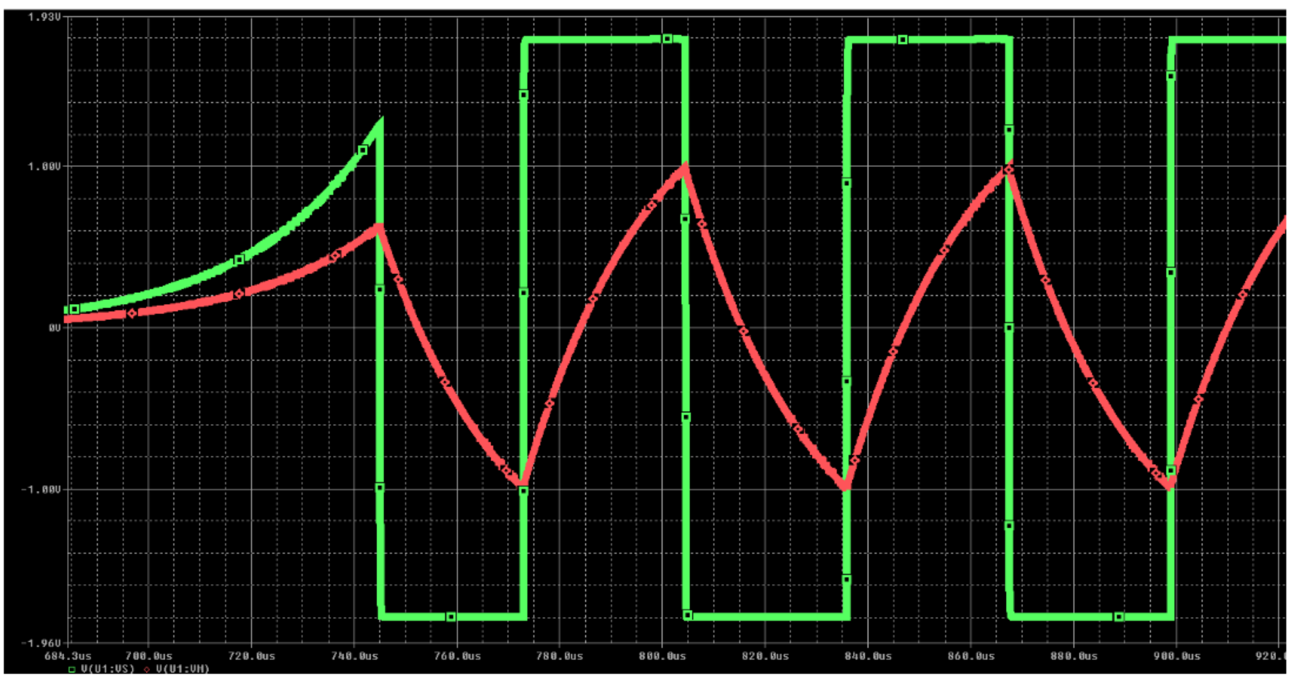


Calculated Period:
T = 55us for C = 50pF
T = 33us for C = 30pF

V_{TH} needs to be ½ of 1.8V

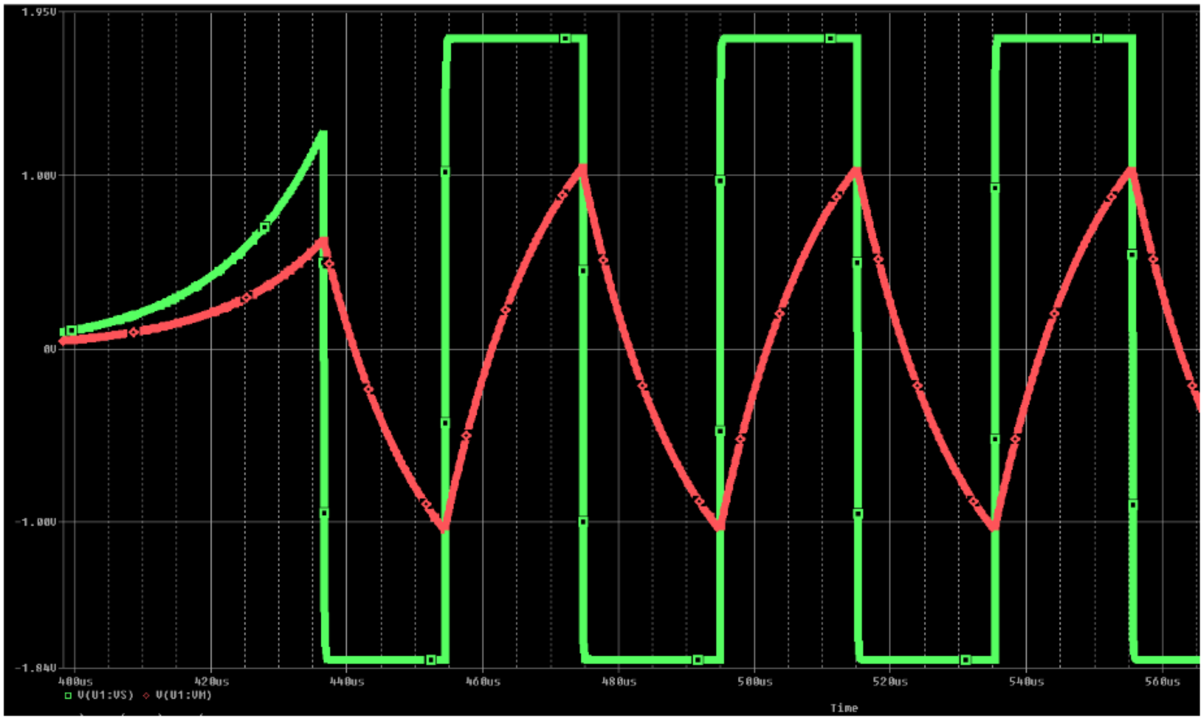
TS881 – Comparator
Operating Voltage Supply: 1.2-5.5V

Figure 14: Relaxation Oscillator Version 2 (C = 50 pF)



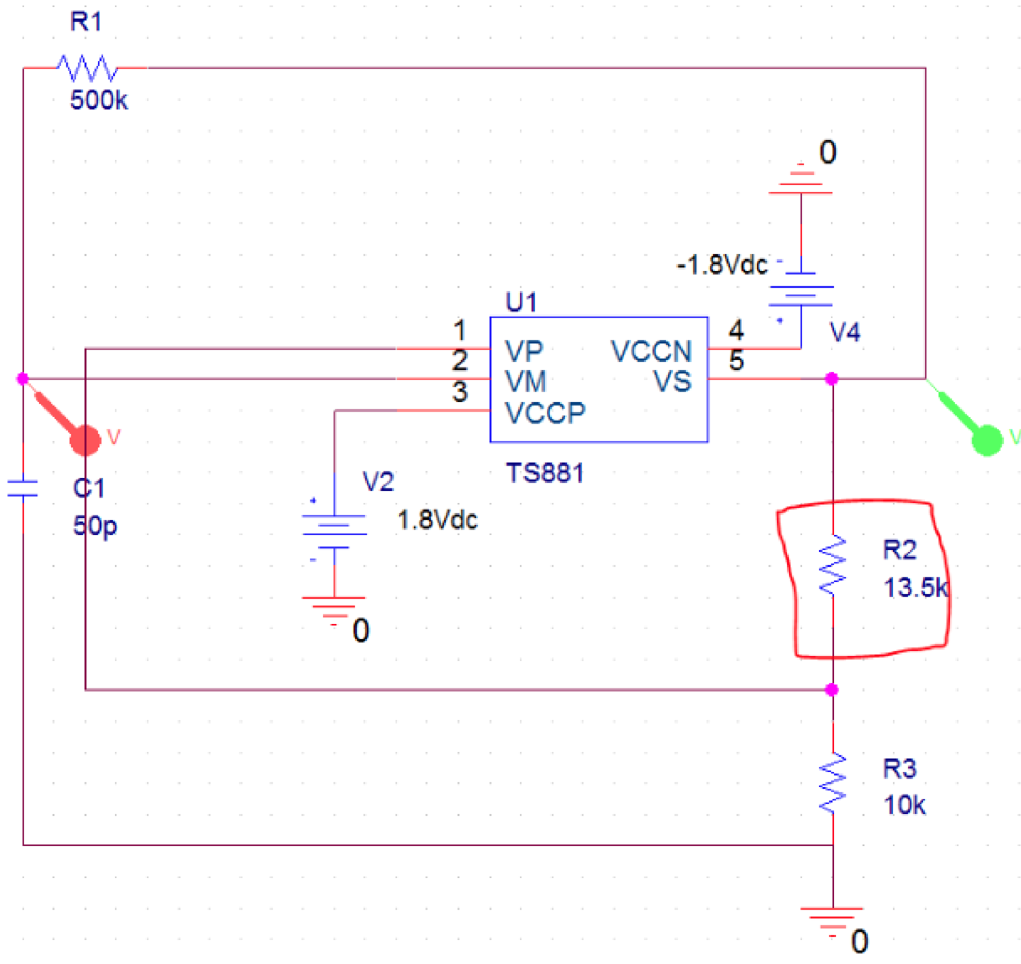
Simulated: T = 62us
Calculated: T = 55us

Figure 15: Relaxation Oscillator Version 2 (C = 30 pF)



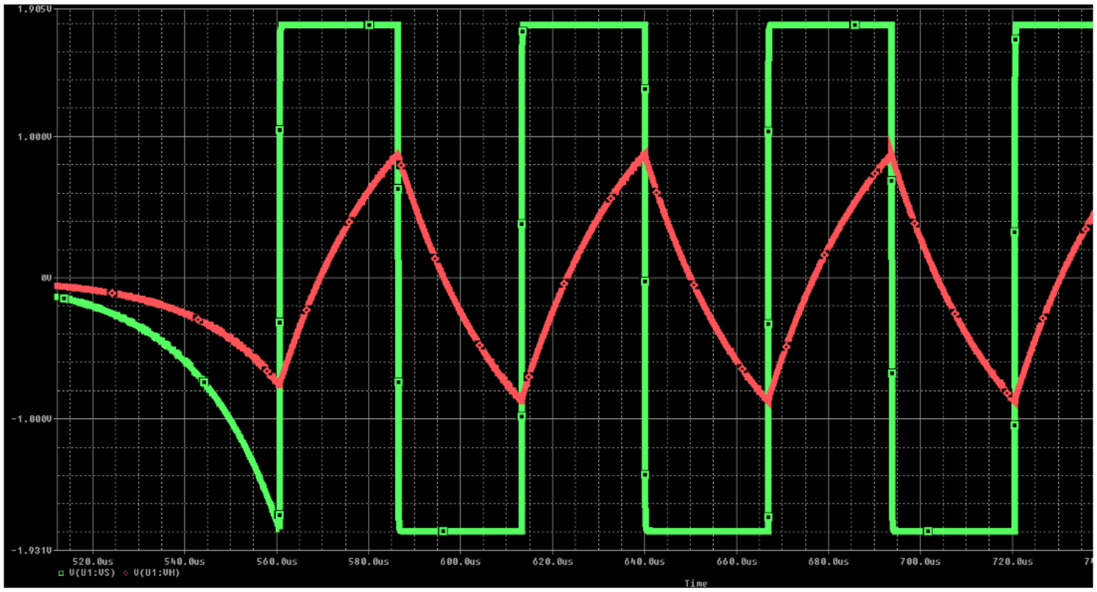
Simulated: T = 40us
Calculated: T = 33us

Figure 16: Relaxation Oscillator Version 2 Schematic Tuned



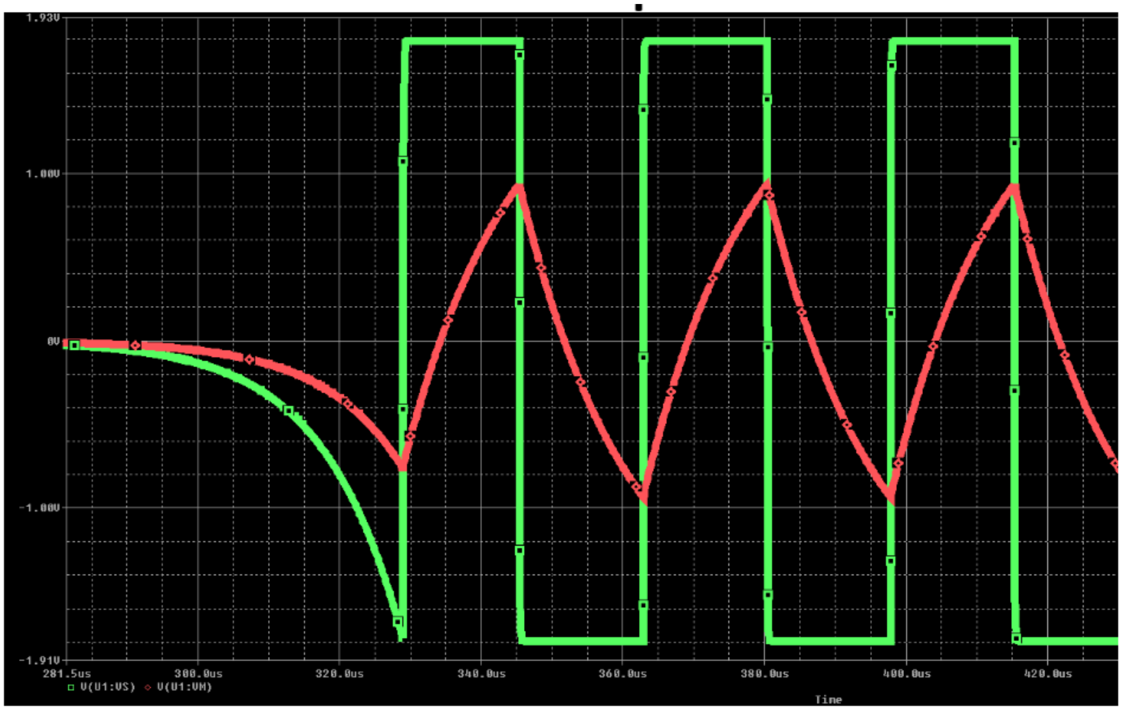
Comments: We tuned the resistor value in order to measure the capacitance accurately.

Figure 17: Relaxation Oscillator Version 2 Tuned (C = 50 pF)



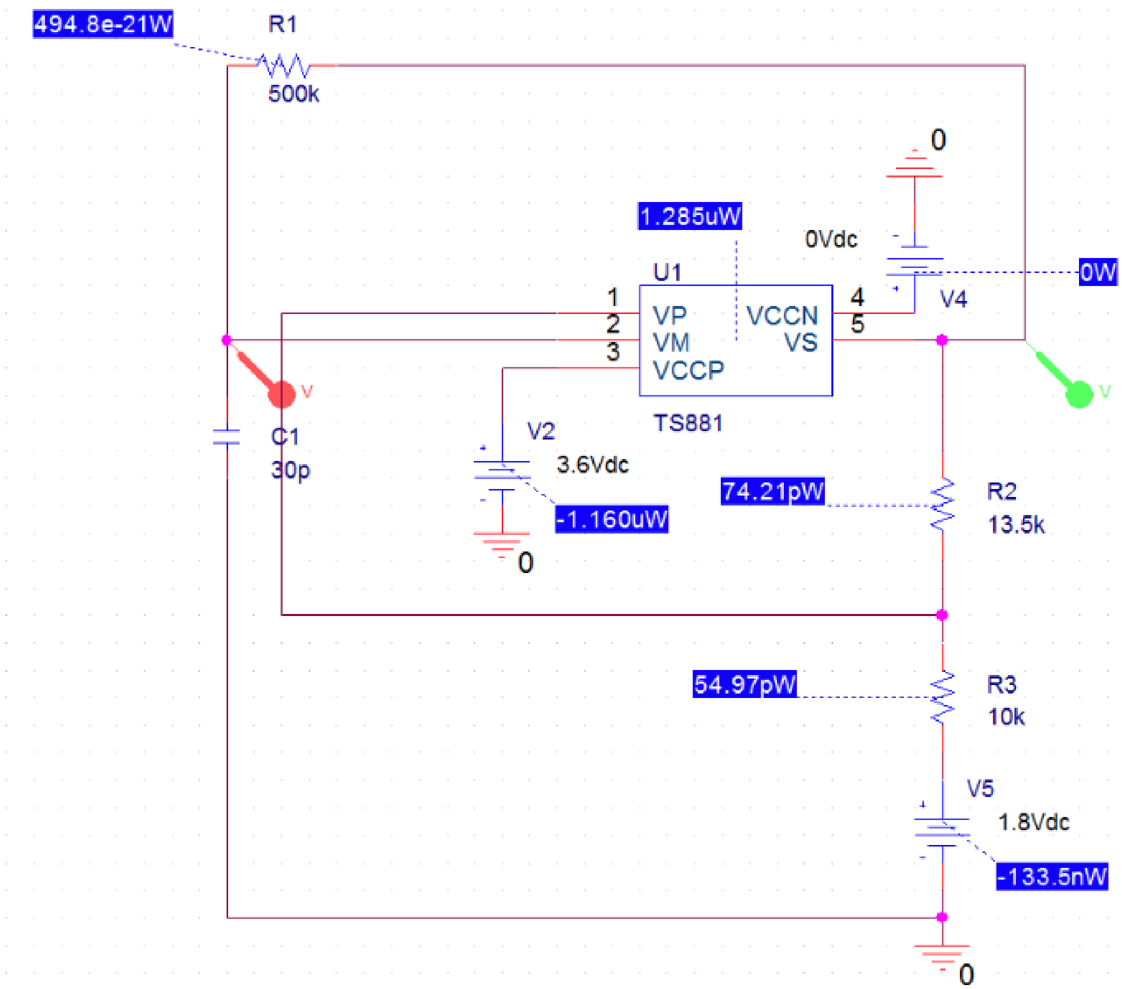
Simulated: T = 53us
Calculated: T = 55us

Figure 18: Relaxation Oscillator Version 2 Tuned (C = 30 pF)



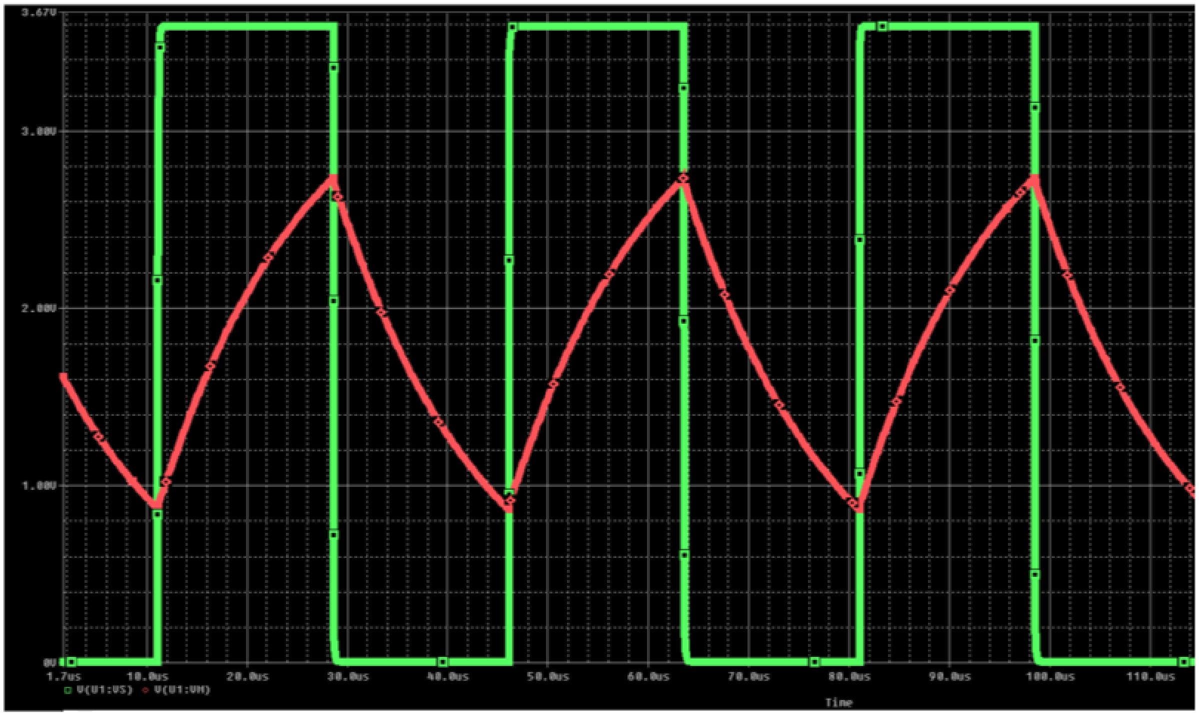
Simulated: T = 35us
Calculated: T = 33us

Figure 19: Relaxation Oscillator Version 2 Schematic Tuned and Shifted



Comments: We shifted the reference voltage on VCCN from -1.8V to 0V. This will allow the output to be in the positive region.

Figure 20: Relaxation Oscillator Version 2 Tuned and Shifted (C = 30 pF)



Simulated: T = 35us
Calculated: T = 33us

4 Closing Material

4.1 CONCLUSION

Capacitance Measuring:

We have been able to design and test the relaxation oscillator version 2 with the STMicroelectronics TS88 comparator IC. The next goal will be to order the TS88 and demonstrate a working prototype on a breadboard. The final goal will be to fabricate a PCB will all surface mount parts that we can demonstrate by the end of next semester.

Antenna Design:

We have been able to get a rough estimate on the amount of received power we would expect for our RF tag. We have also chosen our design for an inverted-F antenna per the DN023 application note from Texas Instruments.

The next goal is to simulate the DN023 inverted-F antenna with ADS software to verify the frequency of operation for the antenna. The final goal will be to order a PCB with this design fabricated on the surface.

Microcontroller and Communication Design:

We have decided on a low power microcontroller to use for our application. We have also decided on our test plan for the communication protocol by using a software-defined radio (SDR).

The next goal is to configure GNU Radio and test the antenna wirelessly. We will then program the microcontroller to communicate with GNU Radio. The last goal will be to use the microcontroller with the all other components in the final prototype.

4.2 REFERENCES

Capacitance Measuring Resources:

Liu, Yili, et al. "Limitations of a relaxation oscillator in capacitance measurements." *IEEE Transactions on Instrumentation and Measurement*, vol. 49, no. 5, 2000, pp. 980–983., doi:10.1109/19.872917.

Tuttle, Dr. Gary. "Non Linear Oscillators." *EE 230 Website*, Dr. Gary Tuttle, tuttle.merc.iastate.edu/ee230/topics/op_amps/non_linear_oscillators.pdf.

"TS881 Rail-To-Rail 0.9 V nanopower comparator." www.st.com/content/ccc/resource/technical/document/datasheet/a2/60/3e/5d/b2/c1/4a/e9/DM00057901.pdf/files/DM00057901.pdf/jcr:content/translations/en.DM00057901.pdf.

Antenna Resources:

Zeng, Miaowang, et al. "A Compact Fractal Loop Rectenna for RF Energy Harvesting." IEEE Antennas and Wireless Propagation Letters, vol. 16, 2017, pp. 2424–2427., doi:10.1109/lawp.2017.2722460.

Kervel, Fredirk. "868 MHz, 915 MHz and 955 MHz Inverted F Antenna." www.ti.com/lit/an/swra228c/swra228c.pdf.

4.3 APPENDICES

None.