MEMS Capacitive Sensing for Motion Tracking
Functional Description and Complete System Block Diagram
Dave Brennan
Advisors Dr. Shastry and Dr. Timpe

Introduction

The main motivation for the capacitive sensing project for Microelectromechanical systems (MEMS) motion tracking was for biomedical applications. MEMS are used in a wide application of devices today such as an accelerometer in a car for crash detection, or such as this project, a biosensor.

The MEMS device of this project contains cantilever beams that oscillate at a natural frequency.

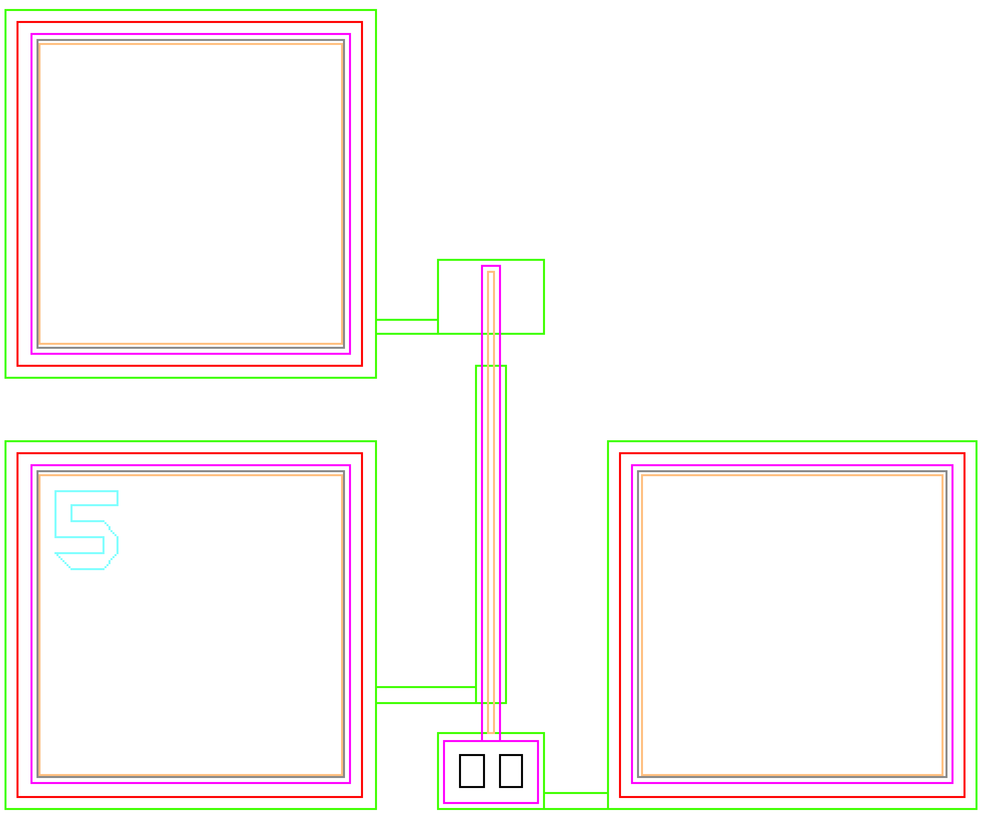


Fig 1 Cantilever Beam on MEMS chip

The natural frequency will change over time as mass is adsorbed on the cantilever beam since frequency is inversely proportional to mass shown in fig 2.

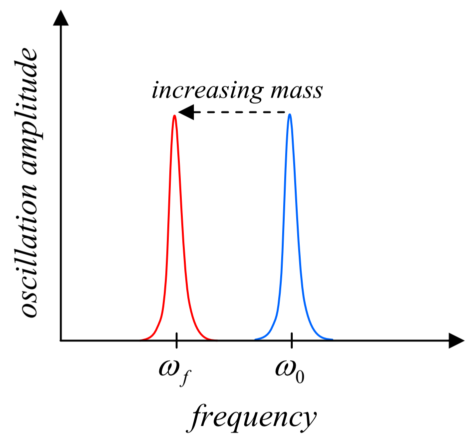


Fig 2 Oscillation amplitude vs. natural frequency

The formula relating natural frequency to mass is given by:

$$\omega_n = \sqrt{\frac{k}{m}} \text{ or } f_n = \frac{1}{2\pi} * \sqrt{\frac{k}{m}} \qquad 1)$$

Where m is the mass, k is the spring constant (design specification), and wn is the natural frequency given in Radian/Hertz and f is the natural frequency given in Hertz. Direct measurement of the mass collected on a microscopic cantilever beam is a challenging task (although this will be verified through biological techniques that are out of the scope of this project), so alternative methods are required.

The main challenge of this project is the capacitors are on a scale that is smaller than most electrical engineering applications acknowledge. For example, the parasitic capacitance of a breadboard is neglected when designing circuitry, but for applications in this project it could be even larger than the capacitance that is desired to be measured creating problems. Table 1 gives some sample MEMS specifications and their capacitances. The possibility of acquiring a capacitive sensor that can measure atto Farads is a possibility while using circuit analysis to determine the capacitance is another possibility. The main challenge of the project will involve identifying (accurately) the value of an unknown capacitance in the atto to fempto Farad range.

Epsilon (F/m)	Length (m)	Width (m)	Area (m^2)	Gap above substrate (m)	Capacitance (F)
8.85E-12					
First design	2.20E-05	6.00E-06	1.32E-10	1.50E-06	7.79E-16
Second design			4.35E-11	6.00E-06	6.42E-17
Third design			1.68E-10	2.95E-06	5.04E-16
Fourth design			1.13E-09	2.00E-06	5.01E-15

Table 1 Sample MEMS capacitance values

Another method of changing capacitance exists in changing the area of the MEMS device as area is directly proportional to capacitance (as opposed to inversely from distance). The capacitive sensor detects capacitive changes as the MEMS device changes its area by a small amount while maintaining a constant distance off the substrate that is anchored over. An example is shown in Fig 2.

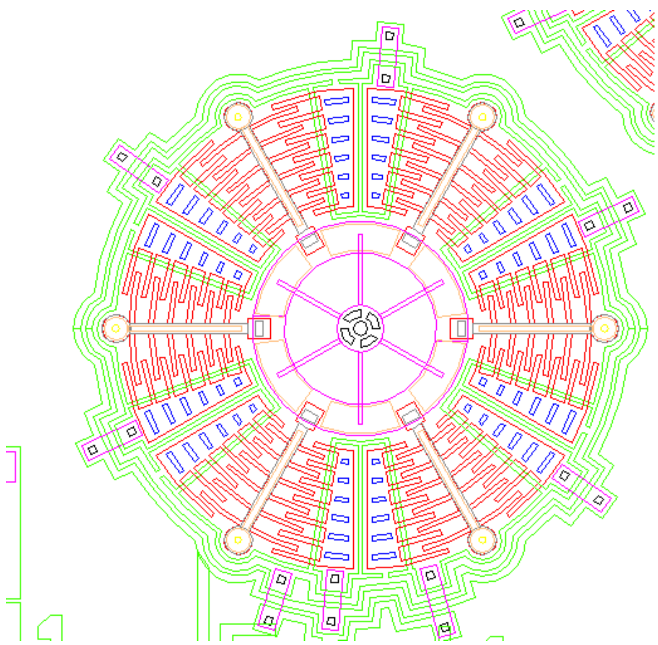


Fig. 3 Rotating MEMS device

Since capacitance is inversely proportional to distance (or directly proportional to area), the distance the cantilever beam (or change of area) moves can be found with:

$$C_0 = \frac{\varepsilon A}{d} \qquad 2)$$

Where epsilon is permittivity of free space, A is the area of the device under consideration, and d is the distance the cantilever beam moves. Since area and distance can change, both cases will be considered for the MEMS device in order to determine capacitance. The more applicable formula is derived in the functional description.

Goals

- Learn how to use the probe station to make connections to a MEMS chip
- Learn how to accurately measure and verify capacitance of the selected MEMS device(s)
- Obtain the natural frequency of the MEMS device
- Accurately track the mass adsorbed by the cantilever beam and have it verified
- If time permits, add a control system that monitors the maximum peak of the voltage wave and adjusts the frequency of the applied voltage signal to ensure the peak is always known
- Minimize the error of all calculations by doing multiple trials

Functional Description

Not all items required for this project are listed, however the known materials are listed below:

- MEMS chip designed by Dr. Shannon Timpe
- Probe station
- Variable capacitor and/or assortment of capacitors
- Waveform generator
- Oscilloscope
- Unlisted materials that become relevant as the project continues on

In order to model the capacitance when the cantilever beam is moving, (3) accounts for the distance displacement

$$C = \frac{\varepsilon A}{d - \Delta d} \qquad 3)$$

The model now has a Δd which is equal to the oscillation distance of the cantilever beam. Unfortunately, since we are working with micro electronics, the parasitic capacitances that could be ignored with larger circuits now tend to dominate the capacitance.

The final equation for the capacitance as a function of distance is given by (4).

$$C = \frac{\varepsilon A}{d - \Delta d} + C_p \qquad 4)$$

The method of dealing with the parasitic capacitance will include some combination of bootstrapping and/or a variable capacitor that can be set to a specific value to eliminate the effect of the parasitic capacitance. Perhaps the most general formula is if instead of a uniform motion between two parallel plates, the motion is instead a function of x and y such as:

$$C = \frac{\varepsilon A}{d - w(x, y)} + C_p$$

This will be perhaps the most common case assuming non-uniform oscillation occurs in a MEMS device.

The Quartz Crystal Microbalance manual provides an interesting way of eliminating the effects of parasitic capacitance. The Lm, Cm, and Rm values would be characteristic inductance, capacitance, and resistance of the MEMS chip while C0 would be the parasitic capacitance.

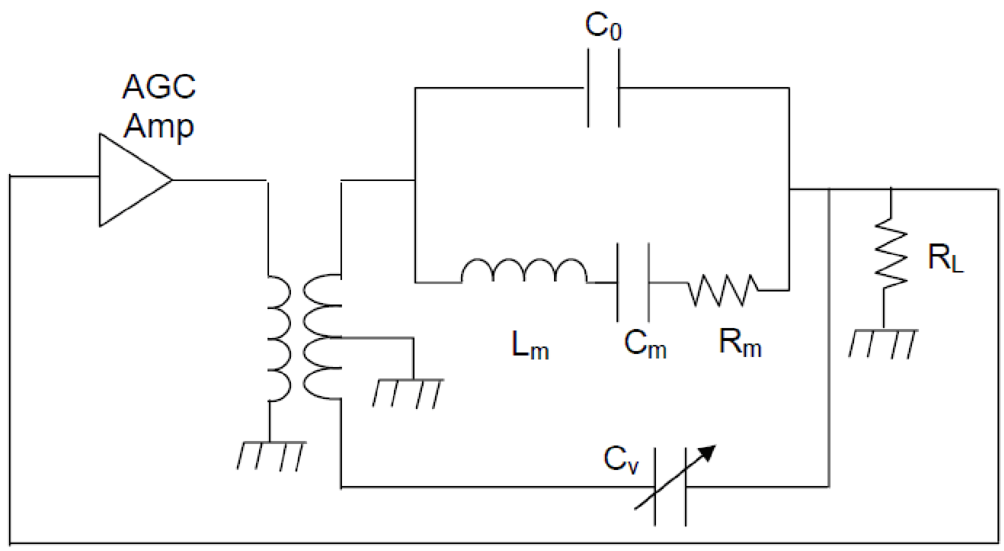


Fig 4 Model of Quartz Crystal Microbalance

The circuit of consideration is connected to a transformer with the center tap grounded. Also connected is a load resistance and a gain in order to oscillate the network. Through circuit analysis (primarily when the current through Co is equal to the current through Cv), the network reduces to the following figure.

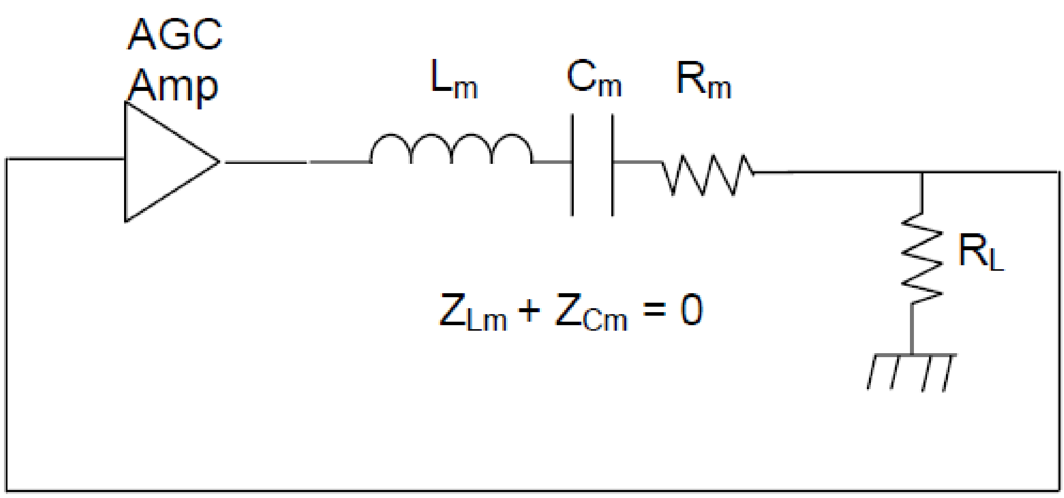


Fig 5 Circuit after reduced with parasitic capacitance tuned out

The peak detection system could be arranged with software or a network of comparators in hardware. The method will depend on the accuracy of initial tests on the MEMS chip. Initially the sweep will be done by hand to monitor the change in natural frequency as the cantilever beam adsorbs mass over time.

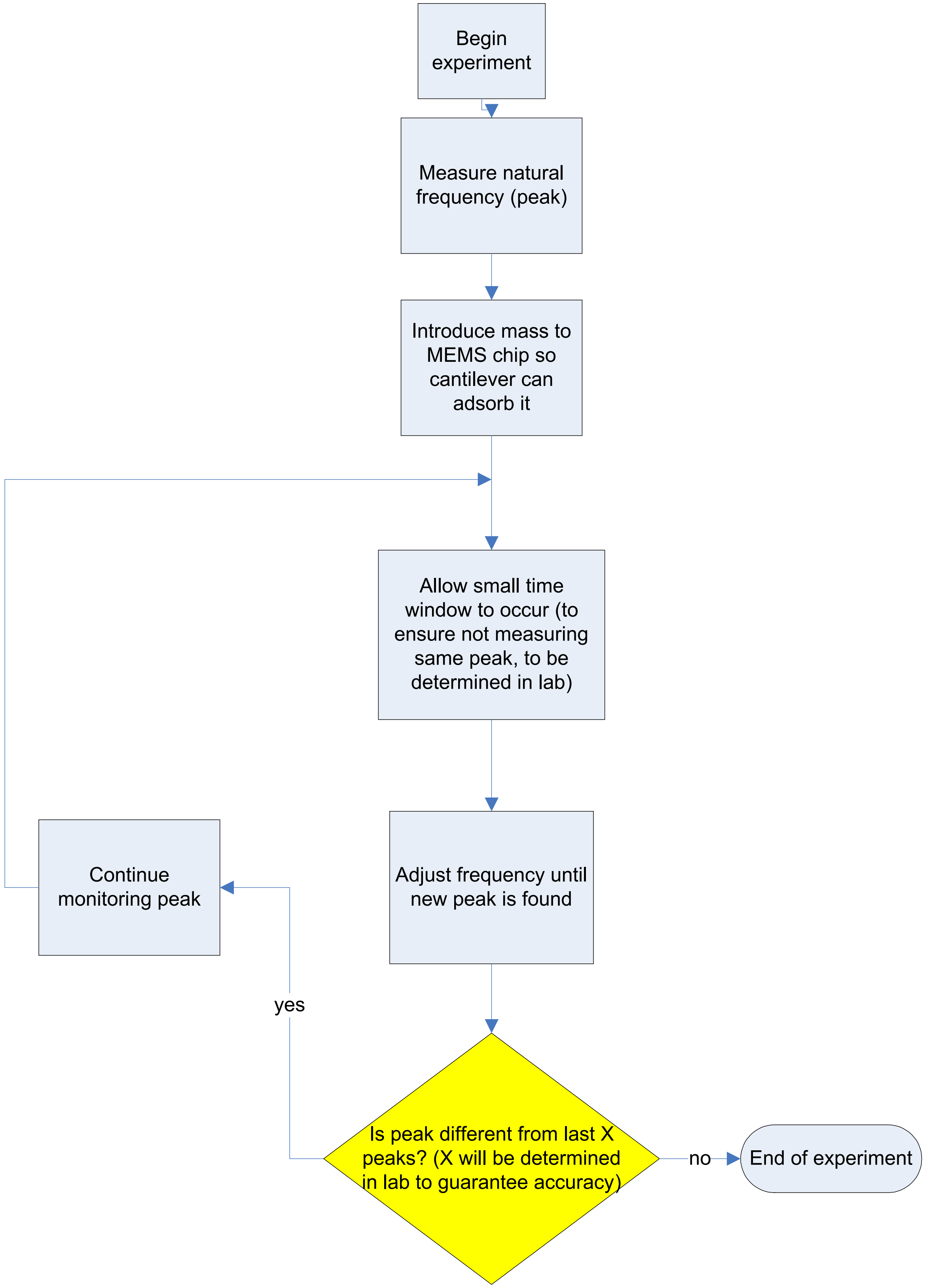
If time permits, a control system will make the peak detection system fully autonomous. A computer will instead analyze the data, and in a specified time interval (most likely in the milliseconds range) adjusting the frequency of the voltage waveform to always maintain the peak. The configuration for the controller will be dependent upon the precision required to maintain the peak as opposed to "chasing the peak". The error should be minimized if the peak is always monitored instead of having to be found multiple times over the course of the experiment.

When the device hits "steady state" that will mean no matter is leaving or bonding with any of the MEMS devices. These tests should be able to be completed in less than a two hour interval of time.

The final step will be to verify that the system is working. The mass will need to be verified using an external method (biological) other than hardware. This will occur in the future after sufficient data can conclude that the device is behaving as desired. The equation relating mass to natural frequency is given by (1). The constant k is the stiffness constant of the cantilever beam and is known from design specifications.

The ultimate goal of this project will be to accurately track mass as it is adsorbed by the MEMS device. This will ultimately allow the possibility of medical advances otherwise unknown simply due to the new knowledge of certain plant compounds interacting with a targeted chip. The goal of this project is to analyze the electrical engineering prospective of the Bradley MEMS project and to complete it using known data instead of revolutionizing new ideas.

Flowchart for capacitive sensing



Work Cited:

- Baltes, Henry, Oliver Brand, G. K. Fedder, C. Hierold, Jan G. Korvink, and O. Tabata. *Enabling Technology for MEMS and Nanodevices*. Weinheim: Wiley-VCH, 2004. Print.
- Elwenspoek, Miko, and Remco Wiegerink. *Mechanical Microsensors with 235 Figures*. Berlin: Springer, 2001. Print.
- Timpe, Shannon J., and Brian J. Doyle. *Design and Functionalization of a Microscale Biosensor for Natural Product Drug Discovery*. Tech. Print.