Capacitance Based Pressure Sensors

By Ashwin Swar, ECE '20

Introduction

Measurement of pressure has been done in many ways depending on the applications. Atmospheric pressure, contact pressure, acoustic pressure are all different kinds of pressures we encounter. Although the basic physics behind them is the same, their measurement is done in very different ways. In this paper we are concerned in measuring the pressure in different regions of the foot as a person walks. To measure the pressure, we have to relate the pressure to some other quantity which we can easily measure. It is also preferable that the quantity being measured is electrical as electrical measuring devices are convenient and can come in all kinds of forms and sizes. Since, pressure causes things to compress, one such quantity that can change due to pressure is the distance between two objects. One of the most basic electrical properties that depends on the distance between two objects is capacitance. We can easily design capacitors and measuring their values can be done by cheaply available integrated circuits like CDCs (Capacitance to Digital Converters) [1]. We will discuss the pros and cons of capacitance based pressure sensing by drawing from our experiences building and using these sensors for collecting foot pressure data.

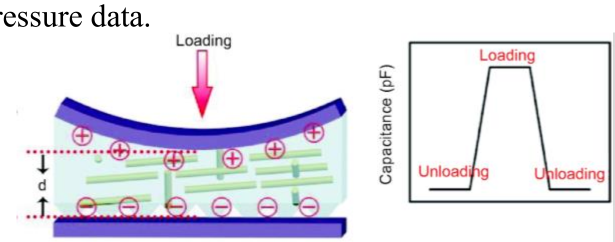

Figure 1: Capacitance based pressure sensor and how capacitance changes with pressure [2]

How it works?

Simply put, a capacitor is a set of two electrodes (plates) that are separated by a material. The physics of a capacitor is such that when the distance between the electrodes is changed the capacitance changes (figure 1). This can be seen from the mathematical relation

$$C = \varepsilon \frac{A}{d} = \frac{Q}{V}$$

where C is the capacitance, ε is the relative dielectric constant of the material, A is the area of the electrodes, d is the distance between the electrodes, Q is the charge stored in the plates and V is the voltage across the plates. If we can change the distance between the electrodes, then we can effectively change the capacitance between the two plates. If the material in between is elastically compressible then when we apply pressure to the plates the distance between the plates decreases temporarily. This change will lead to a change in capacitance. Also, the change in capacitance will be proportional to the change in the distance and hence it will be proportional to the change in pressure. If we are measuring the changes in pressure, then we can directly calculate it by measuring the changes in capacitance. In this way, we can easily build sensors that can measure changes in pressure. Calibration is needed to get accurate pressure values.

Capacitance based pressure sensors vs other forms of pressure sensors

Another way of measuring tactile pressure is by measuring strain. Strain causes changes in electrical resistance of materials which is proportional to pressure. The change in resistance is measured using some kind of voltage divider circuit [3]. This type of measurement has many drawbacks. Firstly, the resistance can also change easily due to other factors like changes in temperature which leads to noisy and erroneous measurements. The strain is also difficult to localize meaning it is difficult to resolve where the pressure is acting. This method also tends to draw power even when the sensor remains passive.

All of these issues are mitigated by capacitive sensing. Capacitance is unaffected by temperature. In fact, it is only affected by physical changes like size of plates and type of material (dielectric), which are easy to control. Pressure measured by using capacitance is also easy to localize—just make the capacitors smaller (up to a certain size) and the spatial resolution will improve. The passive power draw due to capacitor is zero as it is effectively an open circuit. The CDC draws most of the power which can be controlled by using efficient CDCs.

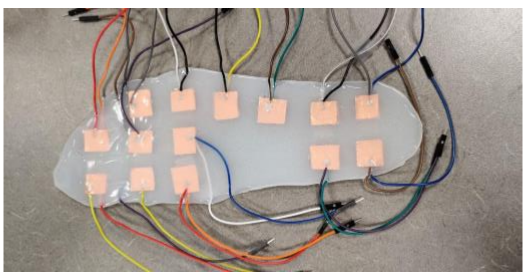

Figure 2: figure showing the insole with capacitive pressure sensors we built

Challenges of Capacitive Sensing

Changes in capacitance due to changes in fringing fields

A parallel plate capacitor has electric field lines fringing outside the plates. This is a well-studied phenomenon [4]. When a finger comes close, it changes this field and thus changes the measured capacitance. This is a problem because due to this, even when we just put our finger on top of the sensor without applying any pressure, the capacitance changed by a lot. This happened to us in our early prototype. To get around this, we had to build pixels that were bigger than before (from 1cm^2 to about 2.25 cm^2). This minimized the contribution of the fringing fields to the total capacitance. So even when these fringing fields changed (when a finger came nearby), the capacitance did not change significantly.

Effects of external charges

External charges have their own fields. They can occur in many ways. In our case, walking creates static charges within the shoe that can interfere with the capacitance reading if the charges get too big. These fields can interact with the electric field in between the electrodes and can cause the capacitance to change even when no pressure is applied. Fortunately, this did not affect our insole sensors in a significant way. But for applications involving strong electric fields, good shielding from external electric fields is necessary for these sensors to function properly.

Capacitance values too small for small sensors

Sometimes, it is desirable to have small pressure sensors. But having small sensor also means the resulting capacitance is going to be so small that it is comparable to extraneous capacitances. This means that the measured capacitance is going to have large error. So, there is a restriction to how small the sensors are going to be.

The CDC (Capacitance to Digital Converter)

The CDC is a small integrated chip that outputs digital values of the measured capacitances. It applies an excitation signal to one plate of the capacitor and measures the charge stored on the capacitor plate. The capacitance is then measured as the charge stored per unit voltage. These have applications in touch screens/pads [5], liquid level monitoring and respiratory rate monitoring. In our project we used AD7745 from Analog Devices. An Arduino was used to control the CDC and collect data.

Project Specific Considerations

For the project we were trying to measure foot pressure data to detect anomalies in gait patterns. For this we built an insole (figure 2) with capacitive sensors. The sensors were built using brass plates. The material that formed the insole as well as the dielectric was Ecoflex, which is a silicone type material that can be easily casted into various shapes. The wires were routed within the body of the sole. The nominal capacitance of the sensors was 3.2-3.6 pF. As discussed earlier making the sensors smaller in area improved the spatial resolution of the foot pressure but the readings also got noisier as the capacitance values of the sensor were comparable to extraneous capacitances. The fringing effects were significant in the first iteration because we used smaller sensors. Using bigger plates helped mitigate this effect. The power draw from the capacitive sensor was very small and most of the power draw came from the CDC which was still very small.

Conclusion

Capacitance based pressure sensors are an important class of pressure measurement sensors. When the sensors are not restricted to be very small (<1cm2), then these sensors have very little drawbacks as compared to other types of pressure sensors. They have low power consumption, can come in various shapes, have accurate measurements and are easy to design which have made them very popular. Through our application of these sensors in measuring foot pressure, we can say that the sensors performed very well and we got reliable pressure data from them.

References

1. Sanjurjo, Javier & Prefasi, Enrique & Buffa, Cesare & Gaggl, Richard. (2017). *A Capacitance-To-Digital Converter for MEMS Sensors for Smart Applications.* Sensors. 17. 1312. 10.3390/s17061312.

2. Shi, R., Lou, Z., Chen, S., & Shen, G. (2018). *Flexible and transparent capacitive pressure sensor with patterned microstructured composite rubber dielectric for wearable touch keyboard application*. *Science China Materials*, *61*(12), 1587-1595.

3. Silva, Anderson Langone, Varanis, Marcus, Mereles, Arthur Guilherme, Oliveira, Clivaldo, & Balthazar, José Manoel. (2019). A study of strain and deformation measurement using the Arduino microcontroller and strain gauges devices. *Revista Brasileira de Ensino de Física*, *41*(3), e20180206. Epub December 10, 2018.https://doi.org/10.1590/1806-9126-rbef-2018-0206

4. Devi, P., Rawat, N., & Pahuja, R. (2016). *Computing the Effect of Fringing Fields on Capacitance.*

5. Kim CC, Lee HH, Oh KH. *Highly stretchable, transparent ionic touch panel*. Science, 2016, 353:682-687

Main ideas derived from:

- Puers, R. (1993). Capacitive sensors: When and how to use them. Sensors and Actuators A: Physical, 37-38, 93–105. doi: 10.1016/0924-4247(93)80019-d

- Soames, R. W. (2006, August 4). Foot pressure patterns during gait. Retrieved from https://www.sciencedirect.com/science/article/abs/pii/0141542585900408.

- Tamm, T., Pärlin, K., Tiimus, T., Leemets, K., Terasmaa, T., & Must, I. (2014). Smart insole sensors for sports and rehabilitation. *Nanosensors, Biosensors, and Info-Tech Sensors and Systems 2014*. doi: 10.1117/12.2045062