Lecture #7

Basic Intent

This lecture is planned to overview pressure sensor technology. It will begin with a review of the basic mechanical equations involved, emphasizing the implications of those equations. Then, some example calculations will be carried out, and some pressure sensing devices will be discussed.

In particular, we will look at an automotive pressure sensor (Kavlico) and learn as much as we can from the way it is designed, built, packaged, and priced. The sensor is set up and made operational in the corner of the classroom, and the students are encouraged to come up and test it in the time following the lecture.

Pressure Sensors

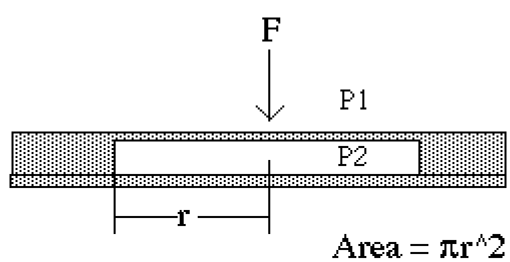

Fig. 1: Simple Pressure Sensor Diaphragm

Aside from some fairly exotic approaches, pressure sensors all operate on the basis of the same principle: the detection of a physical force which arises due to pressure. For example, if a diaphragm separates two regions with different pressures on either side, there will be a physical force on the diaphragm (see Fig. 1) given by:

$$\text{Force} = (P1 - P2)(\text{Diaphragm area})$$

The force is directed from the high pressure region to the low-pressure region. In order to measure this force, we may measure the deflection of the diaphragm with a displacement transducer (such as a capacitive transducer), or we may measure the strain in the diaphragm with embedded strain gauges. In either case, it is to our advantage to have a thin diaphragm in order to maximize the deflection that we plan to measure. There are practical limits to the amount of deflection can measure, as we shall see.

The thickness of the diaphragm is generally also limited by the technology used to manufacture it. For example, metal foil diaphragms are widely used in traditional meteorological instruments (Aneroid barometers). Standard technology for metal foil fabrication is capable of thickness down to a few millimeters at low cost and with good reliability. Metal foils thinner than 1 millimeter are more difficult to make with good uniformity, and bonding of such foils to the remainder of the sensor structure can be difficult. Ceramics and glasses may be used for diaphragms as well. Ceramics casting techniques are capable of reliable fabrication down to thickness of 5 millimeters or so. Ceramics are good because of their reliability at high temperature, and their mechanical and chemical stability. Recently, silicon diaphragms have become popular because of the possibility for thickness below 1 mil, use of implanted silicon strain gauges, and integration with electronics. Silicon also has excellent mechanical properties, including the absence of plastic deformation.

There are several expressions in the textbook which relate pressure and the deflection of stressed diaphragms. These formulae are appropriate if the diaphragms are mounted under tension which causes more stress than the physical pressure. Such mounting is advantageous for guaranteeing linear elastic behavior in metal diaphragms.

Most modern pressure sensors utilize thin silicon or ceramic diaphragms mounted without initial tension. As a result, the expressions in the textbook are inappropriate, and we will mostly discuss other expressions in this lecture. These expressions will not be derived, and the student will not be expected to memorize them. The student should be familiar with their use, and have a general feeling for their structure and its relation to the physical situation.

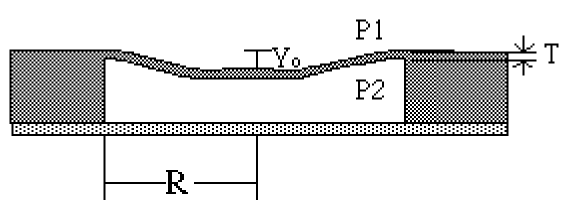

Fig. 2: Deflection in a Circular Diaphragm

The first such expression is the following as shown in Fig. 2, which relates the deflection in the center of a circular diaphragm (**Yo**) to the dimensions and characteristics of the diaphragm, and to the applied pressure:

$$\frac{PR^4}{ET^4} = \frac{16}{3\left(1-\upsilon^2\right)}\frac{Y_0}{T} + \frac{7-\upsilon}{3(1-\upsilon)}\frac{Y_0^3}{T^3}$$

P = pressure difference across the diaphragm

R = radius
E = Young's Modulus
T = diaphragm thickness
v = Poisson's ratio

There are several things to notice about this equation. First, it is nonlinear in **Yo**, and therefore cannot be solved for Yo. The first term represents the stiffness associated with the bending of the diaphragm; the second term represents the stiffness associated with the stretching of the diaphragm. The stretching term introduces a nonlinearity into the physical situation which makes things very complicated.

When manipulating expressions as complicated as the one above, it is generally a good idea to at least verify that the units are correct. We can easily see that the numerator and denominator have the same units on both sides of the equation, so it is at least plausible.

For cases when the deflection is smaller than the diaphragm thickness, the second term is much smaller than the first term, and can be neglected, leaving the expression in the simplified form:

$$Y_0 = \frac{3(1-v^2)}{16}\frac{PR^4}{ET^3}$$

Remember that this expression is only valid for the case of small deflections: meaning that Yo < T.

Lets try an example: Consider a Silicon Diaphragm

E = 1.9 x 10^11
v = 0.25
T = 100 um
R = 1 cm

Assume that there is a pressure difference of 1 atmosphere:

P = 101 kPa = 101 000N/m2

across the diaphragm. What is the center deflection?

We begin by assuming that the deflection is small enough to use the linear expression:

$$Y_0 = \frac{3(1-.25^2)}{16}\frac{(1.01\times10^5 Pa)(1\times10^{-2}m)^4}{(1.9\times10^{11} N/m^2)(1\times10^{-4}m)^3} = 9.3\times10^{-4}m$$

Now, this deflection is 9.3 times bigger than the diaphragm thickness, so our assumption of small deflections is invalid. So, we must use the full expression. After inserting values and simplifying, we have:

$$150 = 16\frac{Y_0}{T} + 7\frac{Y_0^3}{T^3}$$

After some trial and error substitutions (or using a more sophisticated method such as Newton's or Secant method), we find that a value of Yo = 2.5T works well. So, we find that the center deflection is about 250 um, which is still larger than the diaphragm thickness, but is 4 times smaller than the answer we got assuming the linear response. The lessons to learn from this include: 1) 1 atmosphere represents a lot of force 2) Always check your simplifying assumptions.

When the assumption of linearity is valid, we are also given an expression for the membrane deflection at an arbitrary position:

$$Y(x) = \frac{3\left(1 - \upsilon^2\right)\left(R^2 - x^2\right)^2}{16ET^3}P$$

We can see that, at x = 0, this reduces to the earlier expression, and that at x = R, this expression falls to zero, as we would expect, since the deflection at the perimeter has to be zero.

Using these expressions, it is possible to calculate the response of a pressure sensor based on a displacement transducer. For example, if a pressure sensor used an optical displacement transducer, the above expressions could be used to calculate how much a reflective element attached to the center of the diaphragm would move for a given pressure.

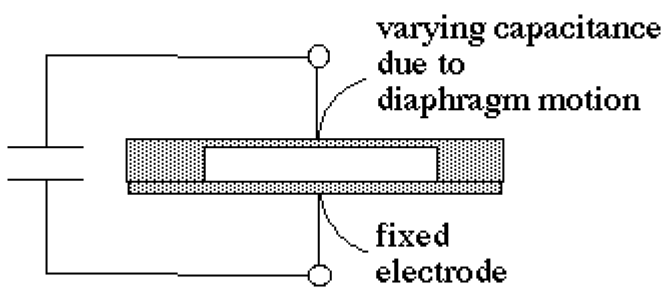

Fig. 3: Capacitance between the diaphragm

A very common and relatively inexpensive measurement approach involves the measurement of the capacitance between the diaphragm and a fixed electrode. As shown in Fig 3, motion of the diaphragm towards the fixed electrode increases the device capacitance. In this case, the capacitance between these electrodes depends on the separation between the diaphragm and the electrode at all positions. This calculation involves an integration of the capacitance at each small location over the entire electrode area. In particular, it involves an expression of the form 1/(d - Y(x)), which is clearly a very complicated mess. Rather than work through the calculus here, we'll just utilize the result:

$$\frac{\Delta C}{C} = \frac{\left(1-\nu^2\right)R^4}{16EdT^3}P$$

where **d** is the original separation between the diaphragm and the fixed electrode.

Example Calculation: Assume a 1 cm radius silicon diaphragm with a thickness of 20 µm and a gap of 50 µm. The initial capacitance between these electrodes is given by:

$$C = \frac{\varepsilon\varepsilon_0 A}{d} = \frac{\left(8.8\times10^{-12}\,C/Vm\right)(1)\left(\pi\left(1\times10^{-2}\,m\right)^2\right)}{\left(50\times10^{-6}\,m\right)} = 5.6\times10^{-11}\,F$$

This is a fairly small capacitance, but it is a good typical value for sensor capacitance. For a pressure difference of 2.5 kPa, the capacitance change is:

$$\frac{\Delta C}{C} = \frac{\left(1-.25^2\right)\left(1\times10^{-2}\,m\right)^4}{(16)\left(1.9\times10^{11}\,N/m^2\right)\left(50\times10^{-6}\,m\right)\left(250\times10^{-6}\,m\right)^3}\left(2.5\times10^3\,Pa\right) = 9.9\times10^{-3}$$

so the capacitance changes by 1% in this case. This is a measurable capacitance change; larger change could get close to the edge of the linear limit. Remember that the expression for the shape of the diaphragm which led to the capacitance change expression is based on the small deflection assumption. To check the validity of this solution, we should calculate the deflection of the center of the diaphragm and compare it with the diaphragm thickness.

If these parameters were to be used for a sensor design to be linear up to 2.5 kPa of pressure difference, this linearity issue would be of serious concern. In a real design, we would probably increase the diaphragm stiffness (smaller R or larger T) to limit the deflection to smaller values.

Throughout all of these calculations, linearity has been a serious concern. Historically, it was necessary to couple the diaphragm deflection to a mechanical amplifier to produce an observable deflection. Because of this, it was necessary to work in the limit of large deflections. The linearity issues were handled by introduction of corrugation into the diaphragm. A corrugated diaphragm, such as the ones used in aneroid barometers allow large amplitude deflections without requiring the membrane to be stretched, since the corrugations may be straightened. There is considerable information in mechanical engineering handbooks relating the shape and distribution of corrugations to the load-deflection behavior of diaphragms. For the purposes of this course, it is generally sufficient to assume that mechanical designs with flat diaphragms which produce deflections up to 10 times the diaphragm thickness may be linearized by introduction of a simple corrugation structure. For still larger defections, accurate calculations, which are beyond the scope of this course, may be necessary.

Another approach to the measurement of forces on the diaphragm is based on measurement of strain in the diaphragm. The pressure-induced deformation of the diaphragm leads to measurable strain changes. The stress induced in a thin diaphragm due to pressure loading is given by:

$$\sigma(x) = \frac{3R^2}{8T^2}\left[(3+\upsilon)\frac{x^2}{R^2} - (1+\upsilon)\right]P$$

This expression is for the radial stress induced on the upper surface by an axial pressure load. Note that the sign of the stress changes from the edge (positive - tensile) to the center (negative - compressive), as you would expect. Also note that there is a location in the diaphragm where the stress is not affected by pressure applied to the diaphragm. Finally, note that the stress is greatest at the edge of the diaphragm, so the edges are the best locations for the strain gauges to be applied.

As an example, we consider a strain gauge pressure sensor sold by **Novasensor**. This sensor is specified for a pressure range of 0 - 2.5 kPa, with a maximum pressure of 25 kPa. Given the fairly small size of its package, we assume that diaphragm has a diameter of 2 mm. Silicon fabrication techniques in use at Novasensor are easily capable of manufacturing diaphragms with thickness of 20 µm. Would such a device give a measurable signal?

$$\sigma(R) = \frac{(3)(1\times10^{-3}m)^2}{(8)(20\times10^{-6}m)^2}[(3+.25)-(1+.25)](2.5\times10^3\,Pa) = 4.7\times10^6\,N/m^2$$

Since

$$\varepsilon = \frac{\sigma}{E}$$

we have

$$\varepsilon = \frac{(4.7\times10^{-6}\,N/m^2)}{(1.9\times10^{11}\,N/m^2)} = 2.5\times10^{-5}$$

Now,

$$\frac{\Delta R}{R} = K\varepsilon$$

so this situation would produce a change in resistance of:

$$\frac{\Delta R}{R} = (100)\left(2.5 \times 10^{-5}\right) = 2.5 \times 10^{-3}$$

This represents a 0.25% change in the resistance value, which is small, but measurable. So, we see that easily achieved device dimensions produce measurable deflections. Can the diaphragm be thinner?

Well, we need to stay below the failure limit for the silicon diaphragm. The specification sheet states that the device must survive pressure signals up to 25 kPa, which is 10 times larger than the case we calculated. By scaling, such a signal would produce a strain of only 0.025%, which is very well below the yield limit in silicon (3%). Then, how much thinner could the diaphragm be?

Strain gauge pressure sensors are very common in industry these days, primarily because the silicon micromachining technology necessary to manufacture decent sensors has been available at very low cost (<$50) for several years. At least a dozen small companies have been in this market for several years, and recently, devices offered by Motorola guarantee that devices of this sort will continue to be available at lower cost and with better performance.

Kavlico Pressure Sensor

Although silicon diaphragm makes an effective pressure sensor, there are other technologies available to compete with the silicon fabrications. In this section, we're going to consider a particular pressure sensor built by Kavlico, Inc., in Moorpark, CA for automotive applications (Fig. 4).

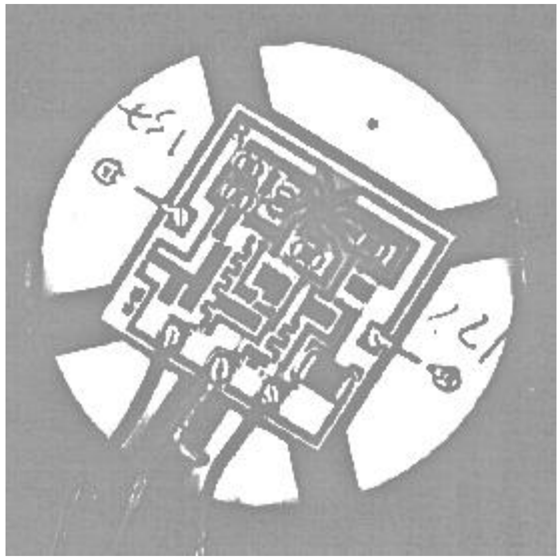

Fig. 4: Kavlico Pressure Sensor Layout

The intended application is measurement of the absolute pressure in the intake manifold. Measurement of this pressure is combined with a measurement of the oxygen in the exhaust stream to regulate the intake of air and fuel into the cylinder.

Because of the chemistry involved in the combustion, an absolute (not relative) pressure measurement is required. Absolute pressure can be measured by measuring relative pressure with respect to a vacuum sealed on one side of the diaphragm. Such a measurement is always a difficult thing to accomplish, because vacuum leaks or outgassing can lead to significant offsets.

It is also important to consider the environment of the measurement. Temperature and humidity can vary over a wide range during engine operation, so accurate control and compensation of these effects is required.

Also, the engine is an electrically noisy place. Pulses of large current flow to the spark plug, and there are electromagnetic disturbances associated with the generators and motors throughout the engine compartment. Therefore, it is necessary to protect the sensor from electromagnetic interference (EMI).

Also, automotive components are now required to feature very long performance lifetimes with very low risk of failure. For example, Chrysler is now requiring component lifetimes of 10 years with failure rates of less than 1 in 10,000. So the sensor design and construction must provide for stable, reliable use over these lifecycles.

Finally, the cost of automotive components is always under competitive pressure. The auto industry is a very big customer (10M cars/year sold in the US). Therefore, there is always a competing manufacturer willing to offer devices at lower cost if profit margins are too large. As a general rule, automotive sensors should cost about $5 each, fully packaged, calibrated, and tested. Devices are allowed to exceed these levels only if the manufacturing process requires the higher cost, and the customer (or the US government) requires the device (see clean air act for an example of legislation inducing the auto industry to include an expensive optional system before the sensors were cheap).

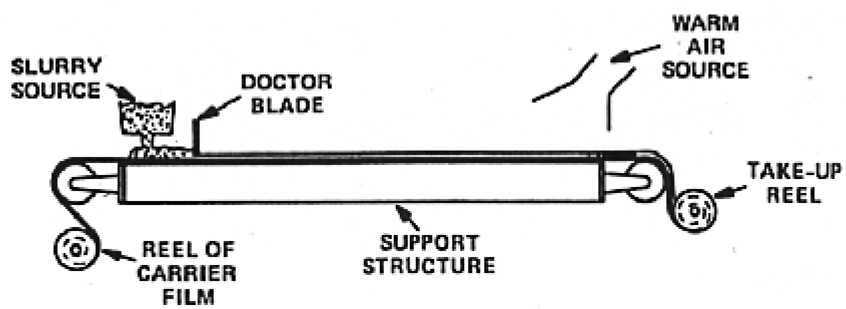

Fig. 5: Processing of Ceramics

Kavlico has been in the business of making automotive pressure sensors for almost 20 years now. As a result, Kavlico was not founded on silicon processing technology. Over these years, Kavlico has optimized a robust, low-cost ceramics manufacturing process (Fig. 5). Based on ceramic tape casting, this process forms flexible sheets of ceramic tape which are easily cut and formed. After cutting, the ceramic parts are fired at high temperature, which results in about 30% shrinkage, and tremendous increases in the elastic constants of the material. The resulting parts may be metallized by screen printing of conductive inks bonded in a glass sealing process, and mounted with circuits for measurement applications.

Kavlico has made a large investment in this mechanical fabrication process, and has trimmed it to the level at which the thin (8-15 mils thick x 2-5 cm diameter) ceramic diaphragms and the substrate can be fabricated with metal electrodes and bonded for about $1.

This technology is naturally appropriate or capacitive pressure sensing. In this case, the diaphragm is sealed with a vacuum reservoir on one side, and a pair of metal electrode patterns are deposited on facing surfaces within the vacuum cavity. The electrode configuration features a common electrode on the diaphragm and a center 'sense electrode' surrounded by a annular 'reference electrode' on the bottom of the reservoir. This configuration allows easy measurement of a capacitance difference, as is useful for linearization and cancellation of temperature effects.

The capacitance between the electrodes needs to be measured with a circuit positioned on the sensor, and this circuit is required by the automotive customers to produce a stable output voltage.

Since the sensor construction is not based on silicon processing, fully integrated electronics is not necessary. Kavlico has extended its ceramics fabrication and screen printing process to the manufacture of a hybrid electronic circuit. Known as a Thick Film Circuit (in contrast to a thin film circuit, which uses 0.1 - 1.0 um metal layers), this structure uses screen printed traces of a conductive ink to make electrical connections. After curing, these conductive ink traces are every bit as stable and reliable as metal traces. They usually feature lateral dimensions of greater than 20um, and thickness of several um.

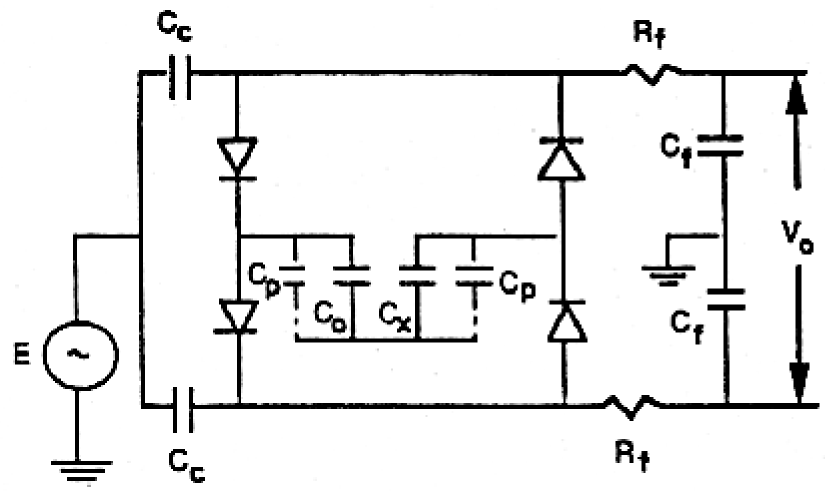

Fig. 6: Quad Diode Circuit Diagram

Discrete electronic parts, such as resistors and capacitors are surface-mounted onto the thick film circuit in a low-cost solder-bump process. Finally, a single application specific integrated circuit (ASIC) is required to carry out the capacitance measurement. Kavlico uses a very common 'Quad Diode' circuit (Fig. 6), which requires the fabrication of a set of 4 well-matched diodes and a sine-wave oscillator. This circuitry is available to Kavlico from an outside vendor as a mm-sized silicon chip, which is also solder-bump mounted on the thick film circuit.

With all the parts and fabrication included, this circuit is assembled and mounted by Kavlico for a cost of about $1.50. This overall approach to low-cost fabrication of moderate circuitry is very common in industry, and is an intermediate step between printed circuit board technology and fully integrated circuitry.

In practice, the sensors which result from the manufacturing process have capacitance which differ by 10-30% from part-to-part. One very important advantage of the carbon ink conductors used in this process is that they are very easily 'trimmed' by focused laser beams, which actually modify the dimensions of gain and offset resistors on the thick film circuit. The trimming step requires connection of the sensor to a vacuum reference, and measurement of the sensor output before and after the laser modifies the circuit. This process is somewhat time consuming, and requires human involvement, and so is expensive (~ $0.5).

Finally, the sensor must be packaged for mounting in the engine. Because of EMI under the hood, it would be nice to package the sensor in a metal housing. However, a metal housing would be too expensive for successful competition, so Kavlico uses a conductive plastic package for physical and vacuum connection to the manifold. This package also serves to protect the circuit from physical and electrical contamination, and is connected to the ground of the circuit. The package costs about $1.

So, the total cost of producing these sensors is nearly $4, leaving a small profit margin. This profit margin must support the other activities of Kavlico, and allow some recovery of the investment in this product. As you can see, this is a tough way to make a living! On top of the economic difficulties are the basic pressures of working on a primary component of an automotive part. Any serious manufacturing problems must be dealt with instantly in order to avoid delays which are very costly for the customer. This need for reliability and continuity creates a difficult environment for a small company to operate.

Despite these constraints and handicaps, Kavlico produces a reliable, high quality product for the automotive industry. After the lecture, I recommend that you come up and test the device a little to get a feel for its behavior and performance.

Since the device is a capacitive sensor, it is sensitive to stray capacitance which can arise due to waving your hands around near the sensor. In particular, note that by actually touching the connections to the electrodes of the capacitive sensor, it is possible to drive the sensor all the way to one of its output limits.

Lets calculate the size of the capacitive signals that this device is measuring:

The sensor dimensions are: diaphragm radius = 1.5 cm, thickness = 250 um, gap = 50 um, pressure signal = 2.5 kPa, E(ceramic) = 4.5 x 10^11 N/m^2, v = 0.2.

$$C = \frac{\varepsilon\varepsilon_0 A}{d} = \frac{\left(8.8\times10^{-12}\, C/Vm\right)(1)\left(\pi\left(1.5\times10^{-2}\,m\right)^2\right)}{\left(50\times10^{-6}\,m\right)} = 1.2\times10^{-10}\,F$$

$$\frac{\Delta C}{C} = \frac{\left(1-\upsilon^2\right)R^4}{16EdT^3}P = \frac{\left(1-.2^2\right)\left(1.5\times10^{-2}\,m\right)^4}{(16)\left(4.5\times10^{11}\,N/m^2\right)\left(50\times10^{-6}\,m\right)\left(250\times10^{-6}\,m\right)^3}\left(2.5\times10^3\,Pa\right) = 2.2\times10^{-2}$$

So the Kavlico sensor is measuring capacitance changes of up to 2%. Measuring such a change with 1% relative accuracy as needed for this application is perfectly consistent with the accuracy that can be expected from this circuit packaged as a thick film hybrid.

Why not use a strain gauge sensor for these applications. One problem is related to the temperature sensitivity of silicon strain gauges, which would need to be compensated very accurately. In fact, Motorola is introducing a device for this application which uses a HC6805 microprocessor to compensate for temperature and other nonlinearities by using a look-up table which is stored on EEPROM memory on the microprocessor. Such an approach is only reasonable for Motorola, since they have already developed the microprocessor technology for different automotive applications.

Kavlico is in a tricky position with their ceramic capacitive device. Competition with Motorola may squeeze the last of the profit out of this market, unless Kavlico is able to reduce its device cost. As a general philosophy, competition with a big company like Motorola is dangerous, because they can afford to lose money in a new market much longer than any small company.

This situation is becoming a common theme in this entire sensor market. Most of the best technologies were introduced by small companies, and these devices were brought to market for applications which could tolerate higher cost (medical), and eventually optimized for larger scale applications. Now that a large application has been demonstrated, bigger companies are tempted to climb in and take over...

Conclusions

Pressure sensors generally rely on the measurement of the deflection of a thin diaphragm. This deflection can be measured by displacement transducers, such as a capacitor, or by measuring the strain in the diaphragm. The strain gauge approach offers good sensitivity to large-medium signals, and is widely available as an inexpensive device. Capacitive sensors are generally 10 - 100 x more expensive, and are intended for applications which offer smaller signals or cannot tolerate the temperature sensitivity of strain gauges. There are many examples of both approaches in the market, and in the research literature.

Despite the heavy dominance of the silicon fabrication devices, it is refreshing to see other technologies being used in the pressure sensing devices. We have explored a particular pressure sensing device, made by Kavlico, for automotive absolute pressure sensor applications. This device features an exciting mix of technologies which are different from the silicon fabrication approaches mentioned the most so far. The mechanical structure is made from tape-cast ceramic parts, the circuit is made from a thick film hybrid, which is patterned by screen-printing, and has surface mount discrete parts added via solder bump bonds. The entire device is packaged, calibrated, and delivered to the automakers in large quantities at cost of near $5/sensor, based on a fairly small profit margin, and within very demanding performance and reliability constraints.

A few pictures considered in development of these pages:

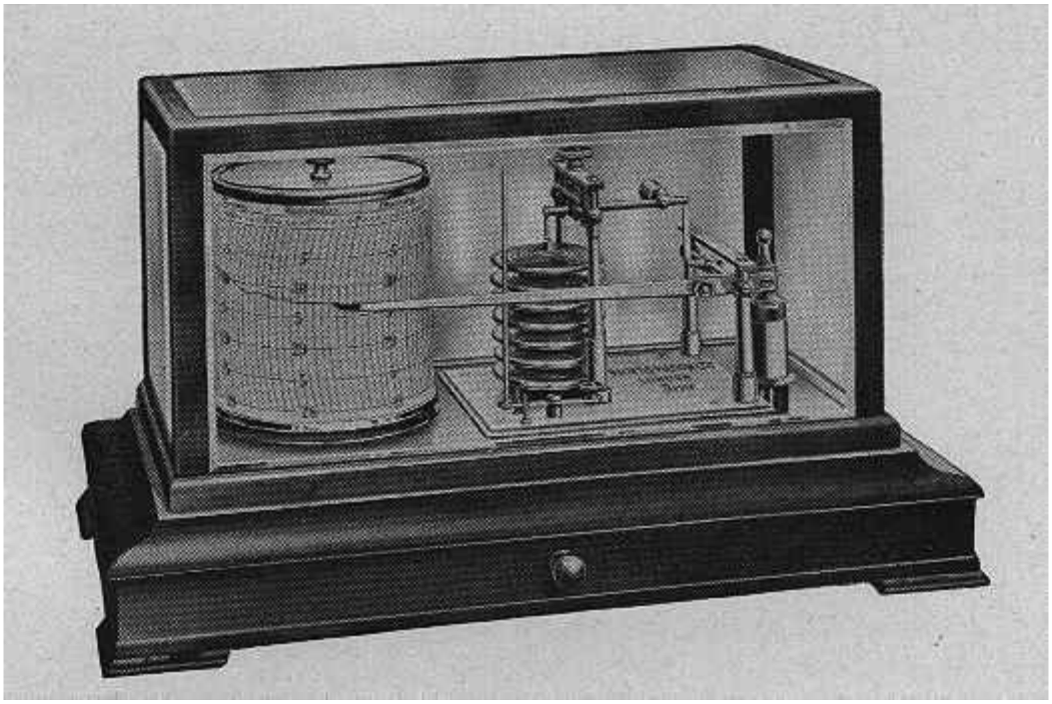

Fig. :Recorder.

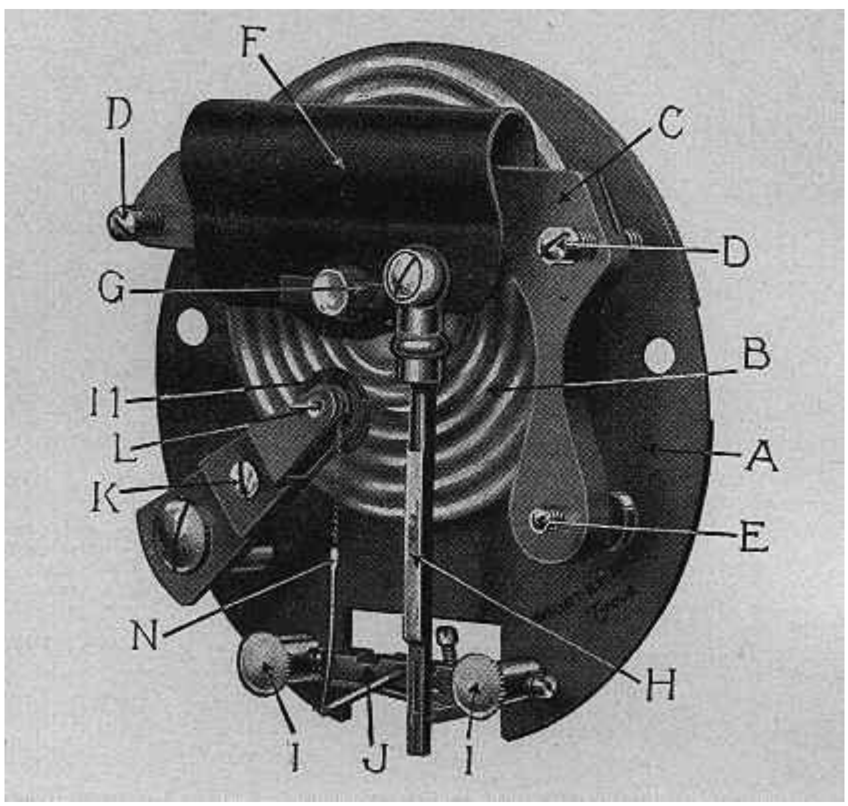

Fig. : Aneroid Barometer.

Fig. :Exhaust.