S2014, BME 101L: Applied Circuits Lab 8: Strain-gauge Pressure Sensor

Kevin Karplus

May 11, 2014

1 Design Goal

In this lab, you will design, solder, and test an instrumentation amplifier to interface a strain-gauge pressure sensor to a microprocessor board running a data acquisition system to record breath pressure as a function of time.

2 Background

2.1 Pressure sensors and strain gauges

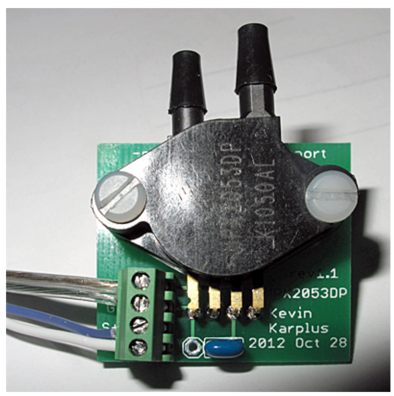


Figure 1: The MPX2053DP sensor, mounted on a *breakout board* that provides easy connection to the pins of the chip and a bypass capacitor to reduce high-frequency noise on the power supply input. Note: the MPX2053DP no longer seems to be made by Freescale, but the data sheets are still available. For a newer design for this lab, one could use the similar MPX2050DP, which has better linearity and temperature compensation, but is otherwise identical. (To save money, one could also use the MPX53DP, which lacks temperature compensation.)

The pressure sensor you are using, the MPX2053DP from Freescale Semiconductor (see Figure 1), is a temperature-compensated strain-gauge pressure sensor which does not include a built-in amplifier.

If I were designing an instrument that needed a pressure sensor, I'd most likely choose one that does include an integrated amplifier, since the extra cost is small and the integrated amplifier makes design easier.

But there are many applications where the integrated amplifier is not available. For example, Freescale's disposable medical-grade pressure sensor, the MPX2300, does not include an amplifier The medical-grade sensor is intended for invasive measurements of blood pressure, and so is made of biomedically approved materials that can be sterilized with ethylene oxide. I considered using the MPX2300 for the course, and even designed a PC board for mounting the part, but the package does not protect the chip well, and I decided the lab needed more rugged parts.

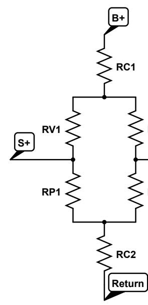


Figure 2: The circuit that Freescale Semiconductor claims is the equivalent circuit for their temperature-compensated pressure sensors. [2]. When I tried measuring the resistances of pairs of wires, I did not get values consistent with this equivalent circuit.

Strain-gauges are also used in other applications than pressure gauges (anywhere that small bending or stretching of solid objects needs to be measured), and most strain gauges don't come with built-in amplifiers. So there are plenty of applications for an amplifier of the type you will design here.

A pressure sensor works by having a membrane separating two compartments: one of known pressure, the other of the fluid whose pressure is to be measured. There are basically three types of pressure sensors: *differential*, *gauge*, and *absolute* pressure sensors. In a differential sensor, both compartments have accessible connections, in a gauge sensor, one of the compartments is the ambient air pressure, and in an absolute sensor, one of the compartments is sealed with a known pressure (often vacuum, since its pressure doesn't change as the membrane moves).

Our sensor is a differential sensor, with two ports that we can connect tubing to, but we'll generally be using it as a gauge sensor, leaving one port open to the ambient air, and connecting a tube to the other port.

When there is a pressure difference between the two compartments, the membrane flexes, bending or stretching some component. A strain gauge on that component changes resistance as a result of the stretching, and the resulting change in resistance is converted to a differential voltage with a Wheatstone bridge circuit (Figure 2).

Warren Schultz writes

> The essence of piezoresistive pressure sensors is the Wheatstone bridge shown in Figure 1 [my Figure 2]. Bridge resistors RP1, RP2, RV1 and RV2 are arranged on a thin silicon diaphragm such that when pressure is applied RP1 and RP2 increase in value while RV1 and RV2 decrease a similar amount. Pressure on the diaphragm, therefore, unbalances the bridge and produces a differential output signal. One of the fundamental properties of this structure is that the differential output voltage is directly proportional to bias voltage B+. [2]

I don't believe that the bridge circuit given by Schultz precisely represents the MPX2053DP sensor we are using, since the resistances I measured on the device were not consistent with this simple circuit—I think that they use a somewhat different temperature compensation circuit, but I've not been able to find it. The basic idea, that the differential voltage between the S+ and S- signals is proportional to the pressure is still correct, and that is all we really need for this lab.

The MPX2053 data sheet gives the output as 40 ± 1.5mV at 50kPa [3], with an input voltage of 10V. The device is *ratiometric*, which means that the output voltage is proportional to the input voltage, so it is better to report the sensitivity as a gain (4mV/V full scale, or 80E-6/kPa). We'll be powering the sensor with about 3.30v, so we expect to see about 23.2mV for a full-scale reading, or 264μV/kPa. [Note: if you are uncomfortable thinking of pressure in kiloPascals, then you may want to use a converter, like the one at `http://hyperphysics.phy-astr.gsu.edu/hbase/pman.html` to convert to non-standard units, like pounds per square inch, mm Hg, atmospheres, and inches or cm of water.]

When I tried inhaling from or exhaling to the tube to the pressure sensor, I got readings of up to -20.5kPa to $+18.2$kPa (assuming I've done my gain computations right, though sustained pressures are more like -17kPa and 17.5kPa. According to one source, the maximum expiratory pressure for young adult men is $233 \pm 84 cmH_2O = 22.8 \pm 8.2$kPa and for young adult women is $152 \pm 54 cmH_2O = 14.9 \pm 5.3$kPa and the maximum inspiratory pressures are $-124 \pm 44 cmH_2O = -12.2 \pm 4.3$kPa and $-87 \pm 32 cmH_2O = -8.5 \pm 3.1$kPa, where the $\pm$ part corresponds to 2 standard deviations [1, Table 9.1, p. 97]. (My inspiratory pressures may be larger than properly measured ones, because I don't have the 2mm leak that is in the standard instrument, to make sure that it is lung pressure and not cheek pressure that is measured.)

These numbers are not particularly close to the $\pm$50kPa of the full-scale reading of the pressure sensor, so you might want to use a higher gain for the amplifier than just what it would take to make the full-scale range of the sensor correspond to the full-scale range of the analog-to-digital converter Having the range of the ADC correspond to $\pm$25kPa is probably reasonable, though you can pick other gain levels.

2.2 Instrumentation amplifiers

An *instrumentation amplifier* is a differential amplifier with very high input impedance on both inputs (pure voltage input, with essentially no current flow). The output of the amplifier is almost purely a function of the difference between the input voltages, with very little influence from from the average of the two inputs—the *common-mode*. An instrumentation amplifier is also good at eliminating noise from the power supply (*power-supply rejection ratio, PSSR*).

The instrumentation amplifier we are using, the INA126P from Texas Instruments, consists of 2 op amps internally, one for each of the differential inputs, as shown in Figure 3. At about \$2.70 per amplifier, these instrumentation amplifiers are much more expensive than op amps (the MCP6004 chips have 4 op amps for only \$0.36).

It is worthwhile to analyze the circuit for the instrumentation amp in terms of the op amps that comprise it. The two inputs of op-amp 1 will both be at V_{in+}, while the two inputs of op-amp 2 will both be at V_{in-}.

We have the following equations from Kirchhoff's current laws for the two inverting inputs to the op amps:

$$(V_{out} - V_{in+})/40k\Omega + (V_{oa1} - V_{in+})/10k\Omega + (V_{in-} - V_{in+})/R_{gain} = 0$$

$$(V_{oa1} - V_{in-})/10k\Omega + (V_{in+} - V_{in-})/R_{gain} + (V_{ref} - V_{in-})/40k\Omega = 0$$

We can solve this pair of equations in several ways, including solving the second one for V_{oa1} and plugging that result into the first equation. After a bunch of tedious algebra, we get the gain equation:

$$V_{out} = V_{ref} + (V_{in+} - V_{in-})(5 + 80k\Omega/R_{gain}) \ .$$

Note that unlike the negative-feedback op amp circuits we've used previously, the output voltage V_{out} is centered at V_{ref}, which is independent of V_{in+} and V_{in-}.

Because both inputs go into op amp inputs, with no feedback connections to the inputs, the instrumentation amp has a very high input impedance (typically $10^9\Omega || 4pF$) and very low input bias currents (typically -10nA). Because the on-chip components have been very carefully matched, the common-mode rejection is quite good (typically a gain of -94dB = 20E-6 for the average of V_{in+} and V_{in-}).

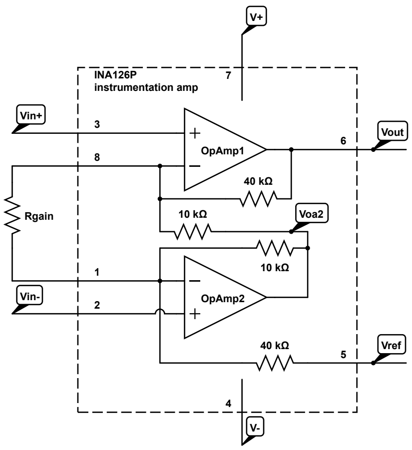


Figure 3: The 2-op-amp instrumentation amplifier relies on a single external resistor to set the gain, with gain $= 5 + 80k\Omega/R_{gain}$.

The inputs need to stay between the power rails, which is guaranteed by the bridge circuit for the strain gauge sensor. We also need to have V_{ref} near the middle of our voltage range, so that both positive and negative pressures can be measured.

Because we are looking at fairly large slow signals with fairly coarse steps on our analog-to-digital converter, many of the important characteristics of the instrumentation amp (the input voltage noise, the slew rate, the bandwidth) are not particularly important for this application.

2.3 Instrumentation amp protoboard

For this lab, you will not be wiring things up on a breadboard, but soldering the circuit onto a *protoboard*—a printed-circuit board that is not designed for a single circuit but for prototyping various circuits (see Figure 4). Soldered wires and components are less likely to work loose than breadboard connections, wires tend to be shorter (and so pick up less noise), and the soldered board provides a more permanent amplifier module.

Because it is considerably more difficult to correct mistakes in design on a soldered board, you need to be much more careful than usual in designing your circuit, drawing up the schematics, and laying out where on the board all the components and wires will be. To help with the layout, I've provided a PDF file at `http://users.soe.ucsc.edu/~karplus/bme194/w13/pc-boards/EKG-proto-rev3.0/EKG-proto-rev3.0-worksheet.pdf` with a representation of the board scaled up to page size for experimenting with different layouts (where resistors and capacitors go, what wires need to be added, . . .). A small version of the PDF is shown in Figure 5.

The protoboard is designed for a single power supply, powering both the INA126P and MCP6004 chips. Since you are going to be reading the output with the Freedom KL25Z board, it makes sense to power the amplifier from that board. The protoboard was originally designed for an Arduino microprocessor board with a 5v power supply, but you should use the 3.3v supply on the KL25Z, since the KL25Z A-to-D converter does not accept voltages outside that range. (Where the prototype board says 5v, you want to connect 3.3v.) Power and ground are provided through screw terminals at the bottom of the

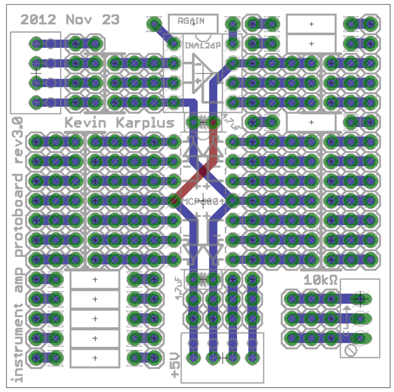
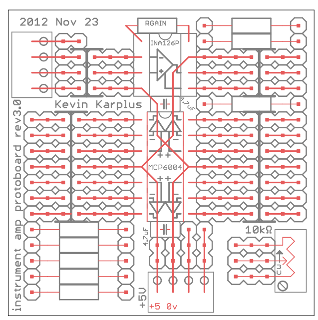


Figure 4: A drawing of the protoboard, showing the printed-circuit-board layers. The red line is a copper *trace* on the top (component side) of the printed-circuit board, while the blue lines are copper traces on the bottom (solder side) of the PC board. The grey lines are silkscreen printing on the top surface of the board. (One can do silkscreen printing on the solder side also, but this board has none.)



11/23/12 8:17 AM f=3.00 /Users/kevin/Documents/eagle/EKG-proto-rev3.0/EKG-proto-rev3.0.brd

Figure 5: Another representation of the board, intended to aid in laying out the components and wires of the protoboard. Note that the +5v and 0v connections at the bottom of the board should actually be to +3.3v and GND on the KL25Z this year.

board—it would make sense for the other two screw terminals in the same block to be used for any other communication needed to the microprocessor board. What information do you want to communicate to the microprocessor? How will it be encoded?

Note that there are two places on the board for 4.7μF bypass capacitors, just below each of the IC chips. Putting bypass capacitors in minimizes problems you might have with noise propagating through the power-supply wiring, and are a standard part of almost all electronics design.

The upper chip is for the INA126P instrumentation amplifier. Each pin of the chip is brought out to 3 connected holes (on the left side of the chip) or 4 connected holes (on the right side of the chip), except for the pair of pins that are intended to be connected to the resistor that sets the gain for the instrumentation amplifier, which have dedicated connections to the R_{gain} resistor immediately above the chip.

The screw terminals at the top left of the chip have two connected holes for each terminal. This block of 4 screw terminals would be a good one to use for connecting to the pressure sensor, which needs 4 wires (power, ground, and the differential signal pair). Note that none of the screw terminals here have a dedicated function—they must be connected to the rest of the circuit with wires, capacitors, or resistors.

There are also uncommitted groups of 3 connected holes on the right-hand side of the board, to the right of the holes connected to the instrumentation amp chip.

The MCP6004 chip has a similar set up to the INA126P chip—power and ground are already wired, and there are 4 connected holes available for each pin. There are also uncommitted groups of 3 holes each just outside the holes for the pins.

There are 8 places on the board for soldering in resistors (in addition to the R_{gain} resistor for the INS126P). Each of these has one extra hole at each end, intended to be used for a wire to connect it to somewhere else on the board.

On the bottom right, there is a place for soldering in a trimpot, should you decide that you need one in your circuit.

Note that there are no dedicated spots for adding capacitors, other than the two bypass capacitors. Because the capacitors in your kit have 0.1" lead spacing, they can be put between any two adjacent (but unconnected) holes on the board. The uncommitted block of 3 holes may prove to be very handy for connecting capacitors.

3 Pre-lab assignment

Start by drawing a block diagram for all the components of the system, from the pressure sensor to the microprocessor. Figure out the characteristics of the signal at the input and output of each block (pressure range, voltage, current, frequency—anything you might need to design the blocks). What sampling rate will you be using on the microprocessor? Will you need any filtering in the amplifier? What gain do you need for the amplifier? Do you plan to achieve that gain in one stage (just the INA126P) or use a second stage op amp to get more gain?

Write down all the design questions and decisions you make. Don't count on remembering them later!

Look up the data sheets for the parts you will be using: the MPX2053DP pressure sensor from Freescale Semiconductor, the INA126P instrumentation amp, and the MCP6004 quad-op amp. Make sure you have a copy of them in front of you when you do your circuit design and layout.

After you have a block diagram, come up with a circuit for each block. Draw your schematic very carefully, with all the pin numbers for the chip labeled. Prepare it for the final report—you want a really clean schematic before you commit to wiring anything. Have both partners check the schematic carefully for errors before going on to the next step.

Based on the "finished" schematics I've seen in your lab reports so far, you need to spend at least twice times as much time checking your schematics for errors as you've been spending so far. Finding the errors while they are on paper is much less effort than finding them once you soldered them in place.

This lab is *not* a tinkering lab—the idea this time is to do the design right the first time, so that you don't have to spend a lot of time debugging.

From the schematic make a *netlist* listing every connection that needs to be made: exactly which pins have to be connected for each node of the circuit. When you have finished the netlist, check it by highlighting a copy of the schematic, one line of the netlist at a time, to make sure that everything on the schematic is included in the netlist and that the netlist does not connect things not on the schematic.

Use the protoboard worksheet to figure out where to place each of the components you need for your circuit (this step is known as "layout"). Draw each wire you need to add on the worksheet (this step is known as "routing"), and verify that the connections you plan there match your netlist exactly. Note that you may end up using different op amps from the quad op-amp chip than you had previously planned (to simplify layout and routing). If so, go back and correct the pin numbers on the schematic and netlist.

Note that some connections on your netlist may be handled by the PC board automatically (such as power to the chips) and not need explicit wires soldered to the board.

Rewrite your netlist as a *wiring* list, listing exactly where parts will be placed on the board and what wires need to be added. Verify your wiring list against the netlist, by highlighting each part of the netlist as you go through the wiring list one line at a time. Double-check your wiring list by doing the same verification against your schematic (perhaps using 2 colors of highlighter: one for components or wires you need to add and one for connections made automatically by the PC board).

Double-check all your pin numbers against the data sheets for the parts. Be particularly careful about swapping the + and − input pins of an op amp!

Do all the pre-lab work carefully before coming to lab. You will probably need three hours or more to solder and test the board. If you do a careful design job ahead of time, debugging will just be looking for soldering errors, not rethinking the whole design.

4 Procedures

It might be worthwhile to connect the sensors up to a 3.3V power supply and an oscilloscope, to make sure that the signals you get from the sensors are what you were expecting when you did your gain calculations.

You have two choices for this lab: either solder up your instrumentation amp board immediately from your design or build and debug the whole thing on a breadboard first, and then transfer the components to the board and solder it. (Only one board needs to be soldered per team.) This amplifier is (barely) debuggable on the breadboard—if you need more gain than this amplifier, the capacitive and electromagnetic noise you pick up from long wiring on the breadboard can cause a lot of problems.

Color code your wires for easier debugging. Use red for +3.3v only and black for ground only. Wires between adjacent holes on the board can be short bare wires. Other wires should be color coded according to function (reference voltage, signal, filtered signal, . . .).

As you add each component or wire to the board, check it off on the wiring list, to make sure you don't omit any. Double check that you are hitting the right hole on the board. It is probably easiest to put in the chips first, then the capacitors and resistors, and do all the wires last. It is a good idea to do short wires before long wires, especially if the wires need to cross.

If you organize your wiring list in the order you plan to solder the connections, it should speed up the assembly of your circuit. (Note: if you re-order your wiring list, you need to go through the check that it is consistent with your netlist and schematic again, to make sure you didn't accidentally lose a connection.)

When you solder wires to the board, measure the wires carefully and make them very short—they should not stick up from the board more than about 6mm (0.25"), except where they need to pass over some other component. Try to minimize the crossing over, in case you need to unsolder and resolder a component or wire.

The four wires from the pressure sensor to the amplifier board (+3.3v, ground, S+, S-) should be color coded and twisted together so that there is little pickup of noise from magnetic fields. The wires from the microprocessor to the amplifier are much less crucial, but color coding them is essential and twisting them together is probably a good idea.

5 Demo and writeup

In lab, you should demonstrate being able measure breath pressure (both positive and negative) and record the breath with the PteroDAQ software. You might want to try some rapid in-and-out pressure changes on the tube—how fast can you get the pulsing to go (using your cheeks is faster than using your diaphragm)? (A higher sampling rate than the default 10Hz may be needed to get a clear view of these rapid fluctuations.)

You can also try pinching the tube shut and pressing on the tube to increase pressure (this is what the long tubes you see across roads to count traffic do). What other pressure fluctuations can you make and record in a piece of flexible tubing?

I might bring in an old aquarium air pump, from which you could record the back pressure and the pressure fluctuations due to the pump motor. Normally one would make a plot of back pressure vs. flow rate for an air pump, but measuring flow rate might be a bit messy in the electronics lab. Describe how you would set up such a test.

In the report, in addition to the usual block diagram and schematic, you should include a picture or drawing of the board to show the layout you used.

You should also include some gnuplot plots of recordings of breath pressure, with the y-axis properly scaled in kPa and with the ambient air pressure at 0. The scaling should be based on the sensor specs and your gain computations—we don't have the time or equipment to do a proper calibration.

6 Design Hints

The building blocks are simple for this lab, but you need to be careful with your gain computation and with your wiring. Sloppy schematics and sloppy layout diagrams will cost you a lot of debugging time.

References

[1] Adam E. Hyatt, Paul D. Scanlon, and Masao Nakamura. *Interpretation of Pulmonary Function Tests: A Practical Guide*. Lippincott Williams and Wilkins, third edition, 2011.

[2] Warren Schultz. Interfacing semiconductor pressure sensors to microcomputers. Freescale Semiconductor Application Note AN1318, Rev 2, 05/2005. `http://www.freescale.com/files/sensors/doc/app_note/AN1318.pdf`

[3] Freescale Semiconductor. 50 kpa on-chip temperature compensated and calibrated silicon pressure sensors mpx2053 series. Freescale Semiconductor data sheet: MPX2053 Rev 9 10/2012.