Chapter 5

Air Pressure

> There is a sumptuous variety about the New England weather that compels the stranger's admiration - and regret. The weather is always doing something there; always attending strictly to business; always getting up new designs and trying them on the people to see how they will go. But it gets through more business in spring than in any other season. In the spring I have counted one hundred and thirty-six different kinds of weather inside of twenty-four hours. Mark Twain, 1876

5.1 Introduction

As the air surrounding the earth is heated by the engine of the sun and cooled by radiation into space, air density differences from place to place result in the air movements we sense as winds. These winds bring us different types of weather, so measuring the air pressure is a very important technique in the prediction of weather.

For example, a sudden drop in air pressure often signals the onset of stormy weather; high pressure signals continuing fine weather.

5.2 Measuring Air Pressure

The classical method of measuring air pressure is the mercury barometer, a column of liquid that is supported by atmospheric pressure, figure **??**.

A closed tube is filled with mercury and then inverted into a reservoir or cistern of the liquid. The liquid column will fall, forming a vacuum above its top surface, until the weight of the column is balanced by the atmospheric pressure. Other liquids can be used, but mercury is attractive because its high density results in a relatively compact instrument. For precise measurements, the observer must carefully determine the height of the column above the level in the reservoir, and compensate for the temperature of the barometer.

In the resevoir, the downward pressure P_m of the mercury column is balanced by the air pressure P_A.

$$P_m = P_A \tag{5.1}$$

The pressure of the mercury column is

$$P_m = \frac{f_m}{a_m} \tag{5.2}$$

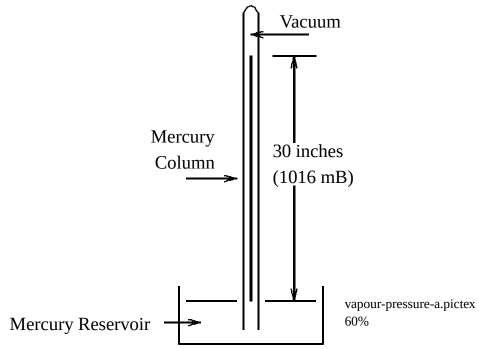


Figure 5.1: Mercury Column Barometer

where

f_m	is the force exerted by the column
a_m	is the cross-sectional area of the column

The column force is

$$f_m = m_m \cdot g \tag{5.3}$$

where

m_m	is the mass of the mercury column
g	is the gravitational constant, 980 cm/sec^2 in the cgs system

The mass of the column is

$$m_m = d_m a_m h_m \tag{5.4}$$

where

d_m	is the density of the mercury, 13.6 g/cm^3 in the cgs system
a_m	is the cross-sectional area of the mercury column
h_m	is the height of the column

Collapsing these equations, we obtain a useful expression for air pressure in terms of the column height and density.

$$P_A = \frac{d_m a_m h_m g}{a_m} \tag{5.5}$$

$$= d_m h_m g \tag{5.6}$$

For example, the so-called standard pressure of physics and chemistry causes a mercury column height of 76 cm. This is an atmospheric pressure of

$$\begin{aligned} P_A &= 13.6 \times 76 \times 980 \\ &= 1013 \times 10^6 \text{dynes/cm}^2 \end{aligned}$$

Pressure Units

A variety of units of pressure have evolved over time. The bar is defined as 10^6 dynes/cm^2 so standard pressure is 1.013 bars. Weather forcasts commonly quote air pressure in millibars, so standard air pressure is 1013 millibars.

In the metric system of measurement, the standard unit of pressure is the pascal, one newton/metre^2. Air pressure is conveniently described in kilopascals, or kPa. Standard pressure becomes 101.3 kPa.

In the English system, the corresponding units are inches of mercury for atmospheric pressure and pounds per square inch for pressure guages.

The values of standard pressure in some common units of pressure are summarized in figure **??**.

1.0	Atmosphere	ATM
1013	millibars	mB
101.3	kilopascals	kPa
76.0	centimetres mercury	cm.Hg
160.2	centimetres water	cm.H_2O
14.69	pounds per square inch	PSI
29.92	inches mercury	in.Hg
406.8	inches water	in.H_2O

Figure 5.2: Pressure Units

The Aneroid Barometer

With careful attention to detail, a mercury column barometer can be very accurate. However, for household use where accuracy is less critical, the aneroid barometer is more practical.

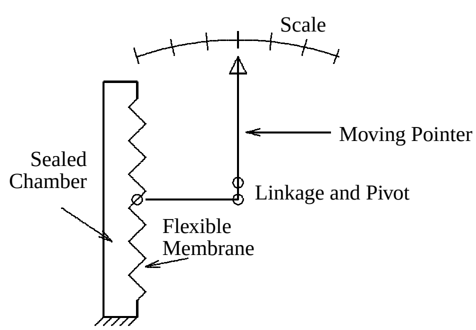


Figure 5.3: Aneroid Barometer

As shown schematically in figure **??**, the sensing element of the barometer is a sealed chamber is equipped with a flexible membrane. As the atmospheric pressure changes, the gas in the chamber increases or decreases in volume. The resultant slight movement of the membrane is mechanically amplified and causes a pointer needle to move.

A typical aneroid barometer scale (unrolled) is shown in figure **??**.

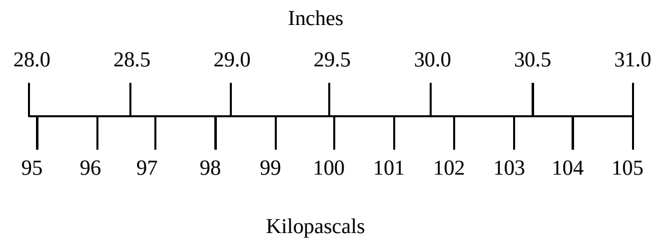


Figure 5.4: Barometer Scale

We will use this in section **??** to determine the requirements for an electronic barometer.

It is also interesting to consider the absolute extremes of measured air pressure, to see if our instrument can cope with them. According to the Canadian Encyclopedia [**?**], the air pressure extremes for Canada and the world are:

Measurement	**Canadian Record**	**World Record**
Maximum	106.7 kPa, Mayo, Yukon Territory, 1 Jan 1984	108.38 kPa, Agata, Siberia, 31 Dec 1969
Minimum	94.02 kPa, St Anthony, Nfld, 20 Jan 1977	87.64 kPa, Eye of Pacific Ocean typhoon June, 19 Nov 1975

Table 5.1: Air Pressure Records

Notice that the record high pressures tend to occur in artic regions, where the air mass is cold and therefore dense. The record low occurred in the eye of a hurricane.

Domestic barometers cannot normally cope with these extremes of air pressures, but we should design for them if the cost penalty is not severe.

5.3 Air Pressure and Altimetry

Air pressure decreases with height, an effect that is used by aircraft altimeters. If the barometer is sensitive enough, a change of altitude by a known amount (an elevator ride, for example) may be used to calibrate the barometer.

First, we need to know the air density, which is given by:

$$\rho = \frac{p}{R \cdot T} \tag{5.7}$$

where

ρ = density of air, grams/cm^3
P = air pressure, dynes/cm^2 (or Kilopascals $\times$ 1000)
R = gas constant for air, 2.87×10^6 cm^2/sec^2 ^{o}C
T = air temperature, ^{o}K

Then the change in air pressure is

$$\Delta P = g \cdot \rho \cdot \Delta H \tag{5.8}$$

where

ΔP	= change in air pressure, millibars
g	= gravitational constant, 981 cm/sec^2
ΔH	= change in height, cm

Example

Find the change in air pressure over a change in height of 30 metres if the air temperature is 20^{o}C and the pressure 1013 kPa.
Solution
From **??** above,

$$\begin{aligned}\rho &= \frac{1013 \times 1000}{2.87 \times 10^6 \times (273 + 20)} \\ &= 1.2 \times 10^{-3} \text{ gms/cm}^3\end{aligned}$$

Then, substituting for ρ in equation **??**,

$$\begin{aligned}\Delta P &= 981 \times (1.2 \times 10^{-3}) \times (30 \times 1000) \\ &= 3532 \text{ dynes/cm}^2 \\ &= 3.53 \text{ millibars}\end{aligned}$$

5.4 Electronic Measurement of Air Pressure

Electronic pressure sensors are used in great numbers in automobile engine control systems. As a result, suitable air pressure sensors have become available at very reasonable cost.

The design shown here is based on the Motorola MPX100AP sensor, a sensor for absolute pressures between 0 and 1000 millibars[1](figure **??**). The pressure sensor is essentially a miniature aneroid barometer. The membrane is a thin silicon diaphram into which has been diffused a network of four resistors in a bridge configuration. The resistors function as sensitive strain guages, changing resistance as atmospheric pressure deforms the diaphram, figure **??**.

The resistance of a conductor is given by

$$R = \rho \frac{l}{A} \tag{5.9}$$

where

[1] We require a maximum pressure measurement of 1050 millibars, which exceeds the maximum rating of the sensor by some 5%. As we will see in the design notes, using a sensor rated for higher pressure would halve the sensor electrical output signal and require double the voltage gain from the sensor amplifier. Even the 5% overload is well below the maximum rating of the MPX100AP (2000 millibars), so we are in no danger of damaging the sensor. Hopefully, its output remains linear in the 5% overload region.

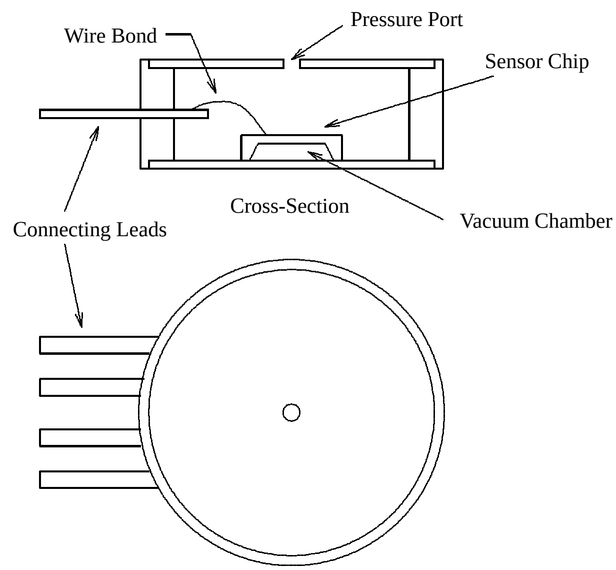


Figure 5.5: Pressure Sensor

ρ	is the resistivity of the conductor
l	is the length
A	is the cross-sectional area

When a resistor is stretched, its length increases and cross-sectional area decreases, both increasing the resistance. In most conductors, this effect is very slight. In the pressure sensors, the resistors are constructed of semiconductor material that shows large changes with small deformations.

When configured as a strain guage bridge, the resistors are located so that diagonally opposite resistors in the bridge change resistance in the same direction, either $R(1+\Delta)$ or $R(1-\Delta)$.

The differential output voltage is then simply $V_{24} = V_{cc} \times \Delta$.

Example

For the MPX100AP sensor, $R = 500\Omega$ and $V_{cc} = 3V$.
If the maximum differential output V_{24}, at full pressure, is 0.06 volts, determine the corresponding values of the bridge resistors at full pressure.

Solution:
From

$$V_{24} = V_{cc} \cdot \Delta$$

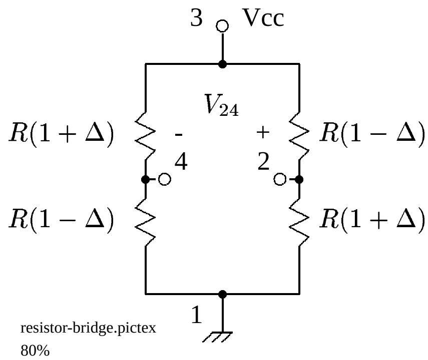


Figure 5.6: Resistor Bridge

so

$$\begin{aligned}\Delta &= \frac{V_{24}}{V_{cc}} \\ &= \frac{0.06}{3} \\ &= 0.02\end{aligned}$$

Then

$$\begin{aligned}R(1+\Delta) &= 500 \cdot (1+0.02) \\ &= 510\Omega\end{aligned}$$

and

$$\begin{aligned}R(1-\Delta) &= 500 \cdot (1-0.02) \\ &= 490\Omega\end{aligned}$$

5.4.1 Sensor Specifications

The key specifications for the MPX100AP pressure sensor are as follows:

Notes:

Pressure Range We will exceed the maximum pressure slightly to 105kPa. This is still well below the burst pressure.

Supply Voltage If the three volt supply is obtained by dropping 2 volts across resistors in series with the sensor, it turns out that the temperature drift of the sensor is substantially reduced (reference [**?**]).

	Minimum	Typical	Maximum	Unit
Burst Pressure	-	-	200	kPa
Pressure Range	0	-	100	kPa
Supply Voltage	-	3.0	6.0	Volts
Supply Current	-	6.0	-	mA
Full Scale Span	45	60	90	mV
Offset	0	20	35	mV
Sensitivity	-	0.6	-	mv/kPa

Table 5.2: Pressure Sensor Specifications

Full Scale Span From these figures, we can determine that the sensor gain varies from 0.45 to 0.9mv/kPa.

Offset This voltage is caused by mismatch of the bridge resistors and appears as a fixed voltage at the output of the sensor.

Supply Current This figure enables us to determine that the bridge resistors are nominally 500Ω.

Sensitivity K_T This is a somewhat redundant statement of the transducer gain, which we determined from the full scale span specification

5.4.2 Barometer Design Issues

There are a number of design challenges which need to be addressed in this system:

Power Supply The available power supply is +5 volts. Either the interface circuit operational amplifier must operate from this or a converter must be available to generate the usual positive and negative voltages for the op amp.

The latter approach requires a DC-DC converter and some method of ensuring that the output of the op amp does not exceed the 0-5 volt range of the HC11 A/D converter input.

Ever mindful of cost, we've chosen the single supply approach. For the DC-DC converter approach, see [**?**].

Amplifier Output Swing The output voltage of a single supply bipolar op amp such as the National LM324 or Motorola MC34074 is very limited: 0.5 to 3.5 volts when operated from a +5 volt power supply. Some CMOS op amps, such as the National LMC660CN, will produce a larger output swing. The data sheet for the LMC660CN shows 0.2V to 4.7V for a +5 volt supply and load greater than 2KΩ, so this is a suitable amplifier for the pressure sensor interface.

Temperature Drift A back-of-the-envellope calculation shows that the sensor amplifier will require a voltage gain in the order of 300V/V or so. Any drift in offset voltage, bias, power supply or resistance values has the potential for being amplified by this large gain to appear as drift in the output voltage. As well, the sensor itself is sensitive to temperature.

All of these temperature effects must be checked to ensure that the circuit functions as a barometer rather than a thermometer. References [**?**] and [**?**] mention the problem of temperature drift, a warning that it must be taken seriously.

As well as designing for low temperature drift, we should choose the minimum voltage gain that meets the requirements, thereby reducing the effect of resistor and voltage drifts.

Calibration The Pressure Sensor Specifications shown in Table **??** on page **??** show that the sensor gain can vary over a 2:1 range, so some sort of calibration procedure will be required. The usual approach is to provide two potentiometers: one for gain and the other for offset. Potentiometers are inherently undesireable in a production design. The part cost is higher than a fixed resistor and a pot requires human intervention for adjustment. It is preferable, if at all possible, that adjustments be done in software.

Subtraction of Bias and Offsets Referring to the Barometer Scale shown in figure **??** on page **??**, the interesting part of the air pressure signal is a 10kPa variation sitting on top of a 100kPa constant pressure. The constant pressure must be subtracted at some point. As well, the output of the pressure sensor bridge is a differential signal sitting on a half-supply common mode signal. The common mode signal must be ignored, so the sensor amplifier must be differential and have a satisfactory common mode rejection ratio.

5.4.3 Barometer Resolution and Dynamic Range

An early and critical decision is the resolution of the barometer, in units of A/D counts per kilopascal of pressure. We'd like a large resolution in order to detect small changes in air pressure. However, higher resolution requires higher voltage gain from the interface and consequent greater sensitivity to a variety of nasty drift signals. Our philosophy should therefore be to make the resolution no higher than necessary.

The face of an aneroid barometer is typically divided into 60 divisions [**?**] and weather broadcasts are typically given to the nearest tenth of a kilopascal. This would imply 100 steps over the 10kPa variation in air pressure. Therefore, we might fix on 1 part in 100 as a suitable target for resolution.

A suitable dynamic range, referring to figure **??** on page **??**, might be 95 to 105 kPa. This does not cope with the extremes of pressure shown in table **??** on page **??**, but will do for routine operation.

5.4.4 Transfer Function

It is useful to characterize the fixed component of air pressure, 100kPa, as P_{ref}, which creates a fixed component of voltage V_{ref} at the input to the microcomputer A-D converter. The variation in air pressure is $\pm\Delta P_a$ around P_{ref}, creating a variation in A-D voltage of $\pm\Delta V_{AD}$ around V_{ref}.

The value of ΔV_{AD} is the product of the resolution, previously fixed at 100 steps, and the voltage per step, 19.5 mv/step, for a 5 volt, 8 bit A-D converter.

Then

$$\begin{aligned} \Delta V_{AD} &= 100 \times 19.5 \times 10^{-3}/2 \\ &= 1.95/2 \\ &= 0.975 \text{ volts} \end{aligned}$$

We'll round this off to ± 1.0 volts.

Now we can fix V_{ref}. It must be large enough that the amplifier doesn't exceed its maximum or minimum output voltages. A good choice is 2.5 volts, halfway between 0 and 5 volts.

With this information, we can draw the transfer function, shown in figure **??**.

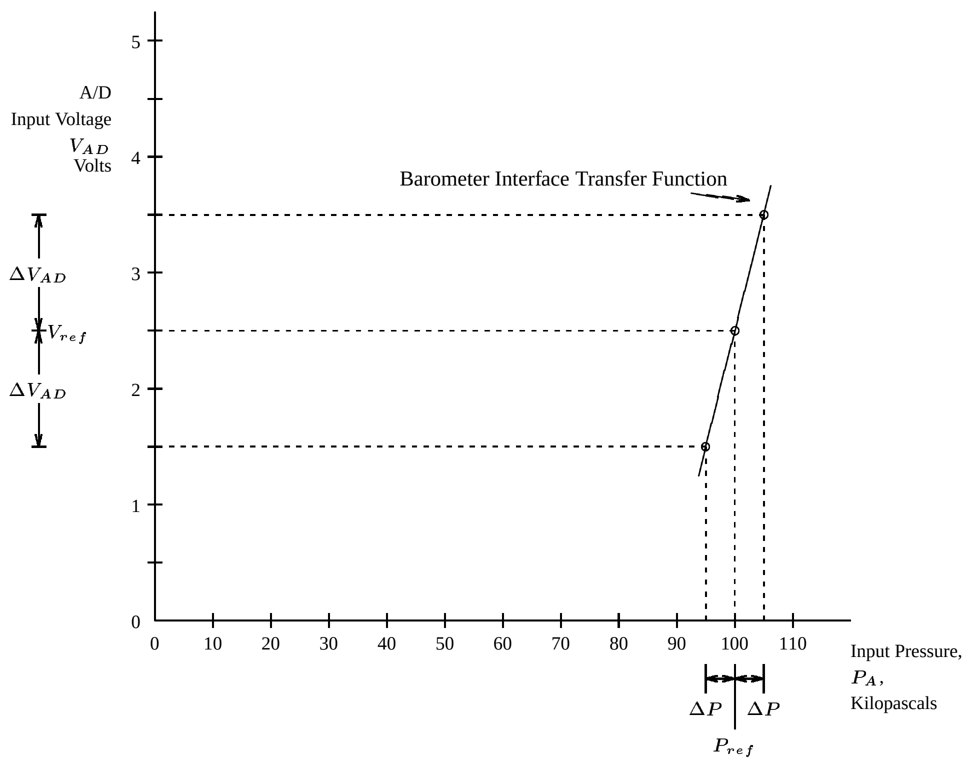


Figure 5.7: Barometer Interface Transfer Function

Substituting two point coordinates in the straight line equation $y = mx + b$, we can solve for m and b, determining that the transfer function is

$$V_{AD} = 0.2P_A - 17.5 \tag{5.10}$$

where

V_{AD}	is the input voltage to the A-D converter
P_A	is the air pressure in kilopascals

Translating the interface transfer function into a block diagram, we have figure **??**.

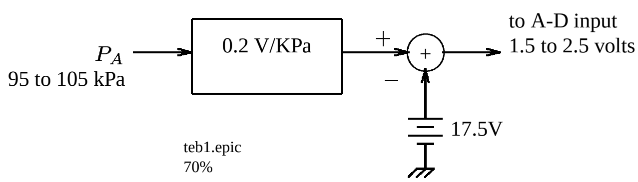


Figure 5.8: Barometer Interface Block Diagram

The typical sensor gain K_T (table **??** on page **??**) is 0.6×10^{-3}, so the amplifier gain must be $0.2/0.6 \times 10^{-3} = 333$ volts/volt as shown in figure **??**.

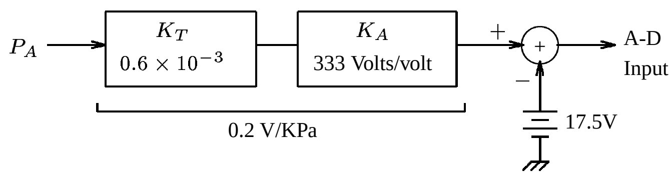


Figure 5.9: Interface Block Diagram, Adding Sensor

There are two practical problems with figure **??**.

- The 100kPa pressure P_{ref} tries to generate a 20 volt signal at the output of the amplifier K_A. This will saturate the amplifier, since it is operated from a +5 volt supply.

- The 17.5 volt offset is difficult to generate in a +5 volt system.

The solution to both problems is to divide the gain K_A into two roughly equal stages, K_{A1} and K_{A2}, as shown in figure **??**.

In this case, the offset voltage V_{OS} is +1.0 volts, easily generated from +5 volts. (Henceforth, for clarity, we shall rename K_{A2} to K_{OS}, the offset gain).

5.4.5 The Barometer Circuit

The final circuit is shown in figure **??**.

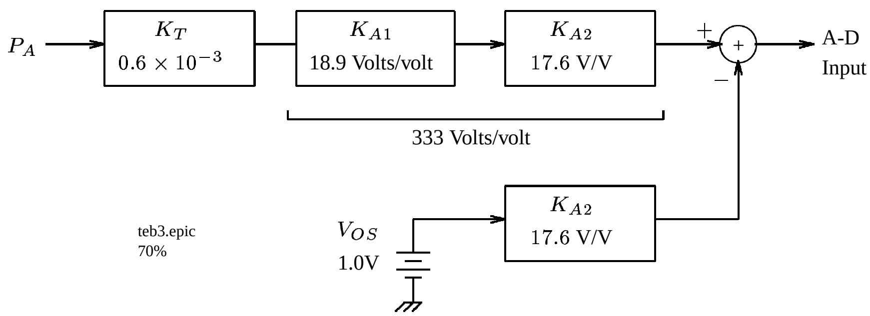
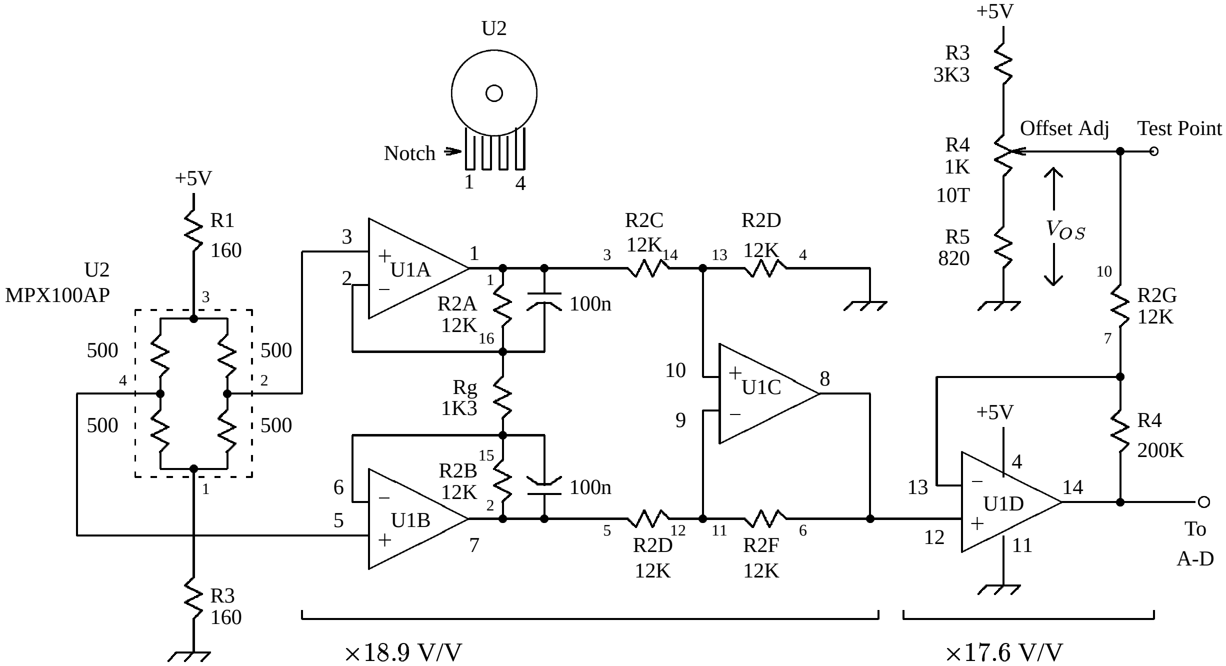


Figure 5.10: Interface Block Diagram, Splitting the Gain



U1	National Semiconductor LMC660CN
U2	Motorola MPX100AP, absolute pressure, hose port
U3	Bourns 4116R-001-123 Resistor Array
	All 12K resistors are part of U3. Small numbers are DIP package pin numbers.
	Discrete resistors must be low temperature coefficient, Philips MRS 25F series or equivalent.
R4	Cermet 10 turn pot, Bourns 3299-1-102 or equivalent.
	Change Rg to alter gain.
R1,R3,Rg	160Ω, 1/4 watt, 1%

Figure 5.11: Barometer Interface Schematic

From the data sheet for the sensor, the resistors in the sensor are 500Ω each and 3 volts should appear across the pressure sensor. Then resistors R_1 and R_2 are 160Ω each.

The instrumentation amplifier, U1A, U1B and U1C provides a high impedance input for the pressure sensor signal. The voltage gain is given by

$$K_{A1} = 1 + \frac{2R_2}{R_g} \tag{5.11}$$

and is set to 18.9 volts/volt. Somewhat arbitrarily, we have chosen R2 as 12KΩ, which makes R_g

$$\begin{aligned} R_g &= \frac{2R_2}{K_{A1} - 1} \\ &= \frac{2 \times 12000}{18.9 - 1} \\ &= 1341\Omega \end{aligned}$$

The nearest standard 5% value is 1300Ω.

If the gain needs to be adjusted, R_g should be changed. To simplify calibration, it should be a fixed resistor, not variable.

In addition to providing voltage gain, this stage removes the 2.5 volt common mode sensor voltage.

The second stage, U1D, subtracts the offset and provides a final gain of 17.6 volts/volt. It could have been implemented with a differential amplifier of gain ×17.6, as shown in figure **??**.

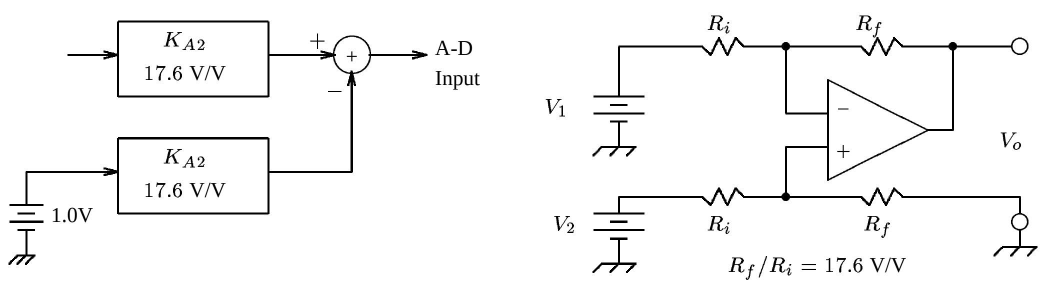


Figure 5.12: Second Amplifier Stage, Differential

However, if we're willing to tweak the voltage at the non-inverting input, we can simplify the circuit as shown in figure **??**.

By superposition, the output voltage is

$$kv_o = -\frac{R_f}{R_i}v_1 + (\frac{R_f}{R_i} + 1)v_2 \tag{5.12}$$

where $R_f = 200K$ and $R_i = 12K$ to obtain a non-inverting gain of 17.6V/V and an inverting gain of 16.6V/V for this circuit. Then V_1, the offset voltage, should be set to $18/16.6 = 1.084$ volts.

The final block diagram is shown in figure **??**.

For good common mode rejection, the resistors of the differential stage U1C are from a resistor array. All other resistors must be low temperature film, ±50ppm temperature coefficient. The offset pot should be cermet for low drift.

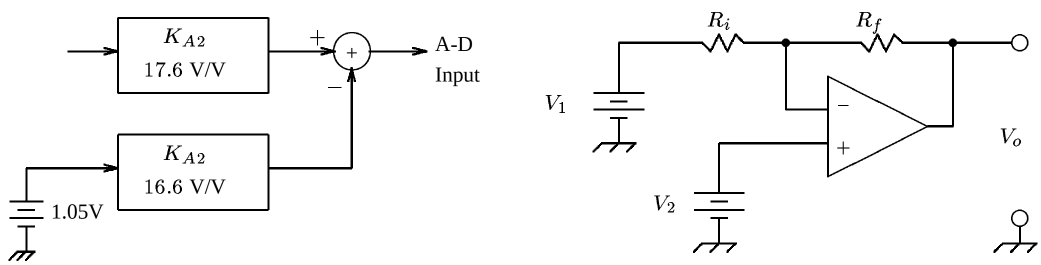


Figure 5.13: Second Amplifier Stage, Simplified

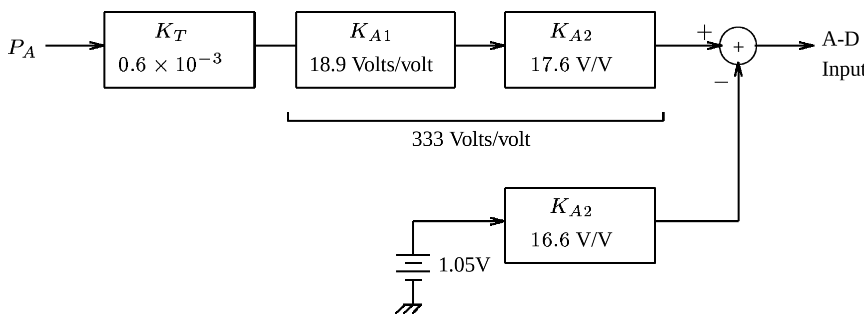


Figure 5.14: Complete Block Diagram

5.4.6 Barometric Software

In section **??**, we established the transfer function of the system, relating the atmospheric pressure P_A to the input voltage of the A-D converter, V_{AD}. Equation **??** was given as:

$$V_{AD} = 0.2P_A - 17.5 \text{ volts/kPa} \tag{5.13}$$

We may rewrite this as

$$V_{AD} = K_{TF}P_A - V_{OS}K_{OS} \text{ volts/kPa} \tag{5.14}$$

where

K_{TF}	is the gain of the transfer function in volts/kilopascal
K_{OS}	is the offset gain, in volts/volt
V_{OS}	is the offset voltage, in volts

The transfer function gain K_{TF} is the product of two components: the sensor (transducer) gain K_T, and the amplifier gain K_A. Then substituting $K_T K_A$ for K_{TF} in equation **??**,

$$V_{AD} = K_T K_A P_A - V_{OS}K_{OS} \text{ volts/kPa} \tag{5.15}$$

We have one final constant to consider. Ultimately, we would like to relate the A-D reading, N_{AD}, to air pressure. We do this with the relationship

$$V_{AD} = N_{AD} K_S \tag{5.16}$$

where K_S is the step size of the A/D, in volts. For an 8 bit A-D converter operated from a 5 volt supply, the value of K_S is $5/256 = 19.5 \times 10^{-3}$ volts.

Substituting $N_{AD}K_S$ for V_{AD} in equation **??** we have

$$N_{AD}K_s = K_T K_A P_A - V_{OS} K_{OS} \text{ volts/kPa} \tag{5.17}$$

Solving for atmospheric pressure P_A we obtain the equation that the software must use to find atmospheric pressure:

$$P_A = \frac{N_{AD}K_s + V_{OS}K_{OS}}{K_T K_A} \tag{5.18}$$

where

P_A	is the air pressure, in kilopascals, to be calculated by the computer
N_{AD}	is the A-D reading
K_S	is the step size of the A-D converter, in volts. In this system, it is 19.5×10^{-3} volts
V_{OS}	is the offset voltage, in volts This value will depend on the offset value that is adjusted into the hardware to set the 100 kPa output to 2.5 volts, and is set at calibration.
K_{OS}	is the offset gain, set at 16.6 volts/volt.
K_T	is the gain of the pressure transducer, nominally $0.6 \times 10^{-}3$ volts/kilopascal, set precisely at calibration.
K_A	is the gain of the amplifiers in the interface, about 333 volts/volt for this system.

The transducer gain K_T and the offset voltage V_{OS} must be determined in order that equation **??** contain sufficient information that the computer program can relate A-D reading N_{AD} to air pressure P_A.

5.5 Barometer Calibration

In this section, we develop methods of calibrating the electronic barometer. We shall look at two manual methods of calibration, and then an automatic method that eliminates the offset potentiometer and the need for human intervention in adjusting it.

5.5.1 Approximate Method

Calculating Sensor Gain K_T

In this method, set the potentiometer R4 so that the voltage into the A-D converter is within its operating range. Then measure the offset voltage V_{OS} at the test point shown on figure **??**, and the current reading of the A-D converter N_{AD}. (You can obtain this from the microprocessor or from the voltage V_{AD} into the A-D).

The the current value of air pressure P_A may be obtained from a weather broadcast. The values of amplifier gain K_A and offset gain K_{OS} are known, since they are determined by fixed resistor ratios.

This is sufficient information that equation **??** may be used to solve for the unknown variable, transducer gain K_T.

Setting Offset Voltage V_{OS}

Once K_T is known, the offset voltage V_{OS} may be adjusted to its correct value. To do this, again use equation **??**. This time substitute the newly-found value for transducer gain K_T together with the known values for step size K_S, amplifier gain K_A and offset gain K_{OS}.

We also know that an air pressure of 100kPa corresponds to an A/D input count of 125 (halfway between 0 and 255).

5.5.2 Accurate Method

The calibration method of section **??** is only approximate because it assumes amplifier and offset gain values, based on nominal resistor values. A more accurate method of determining transducer gain is to apply a known change in pressure ΔP_A to the sensor and observe the corresponding change in A-D input voltage, ΔV_{AD}. The ratio of these two is the slope of the transfer characteristic:

$$\frac{\Delta V_{AD}}{\Delta P_A} = K_T K_A \tag{5.19}$$

A suitable apparatus for generating a known change in pressure is shown in figure **??**. The liquid is water, laced with red food colouring to make it visible. The tubing is flexible plastic hose available from the local hardware store. The hose is filled with water so that it forms a U shape.

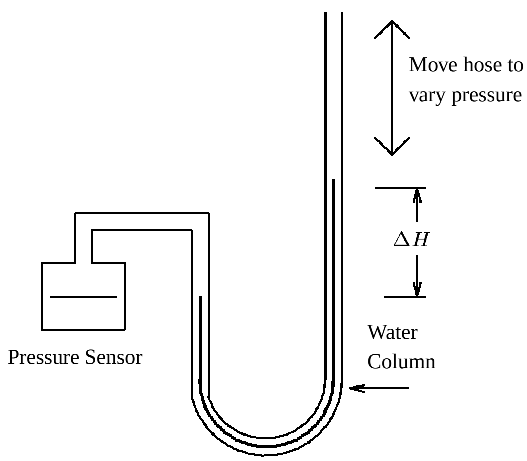


Figure 5.15: Water Manometer

The right side of the manometer is raised or lowered to create a height differential of ΔH. The resulting pressure may be determined from figure **??** on page **??**. For example, a pressure differential of 2 kilopascals may be created by a height differential of

$$\begin{aligned} \Delta H &= \frac{5}{101.3} \times 160.2 \\ &= 7.9 \text{ cm} \end{aligned}$$

Once the transducer-amplifier gain $K_T K_A$ is determined, the current air pressure P_A and corresponding A-D reading N_{AD} may be used in equation **??** to solve for the offset term $V_{OS} K_{OS}$. Finally, the offset voltage V_{OS} may be set as in the approximate procedure.

Once the values of the various terms in equation **??** are known, they may be entered into the computer equation that displays the current air pressure.

5.5.3 Automatic Calibration

If the current air pressure is known and the pressure interface is constructed with fixed resistors, then it should be possible for the microprocessor to read the A-D converter and determine the calibration constants automatically. This need only be done once: the constants are written into EEPROM and are not changed unless the system is re-calibrated.

Unfortunately, there is a problem. The large variation in sensor gain coupled with the high gain of the amplifier section will cause the amplifier to saturate or cutoff unless the offset is adjusted correctly. In section **??** the operator did this manually.

If the microprocessor can be provided with the means to adjust the offset so that the amplifier is operating in its linear range, the microprocessor can determine the calibration constants for its computer program. This may be accomplished by a D-A converter, controlled by the microprocessor, that generates the offset voltage V_{OS}. It turns out that modest resolution is acceptable. As a result, the D-A converter circuit is quite simple and may be driven by a microprocessor parallel port.

The D-A Converter

The schematic of a suitable type of D-A converter, a voltage switching converter, [**?**] is shown in figure **??**.

p-dtoa.epic
70%

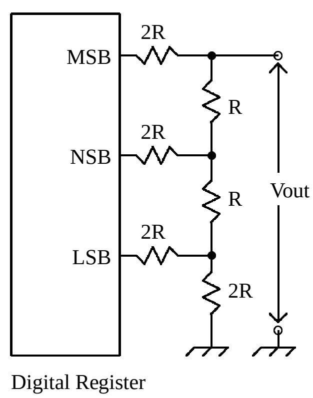


Figure 5.16: Digital to Analog Converter

If the MSB and NSB are both at 0 volts and the LSB is at +5 volts, we may determine the effect on V_{out} by repeatedly applying Thevenin's theorem to the divider circuit. Then $V_{out} = 0.625$ volts. Similarily, the NSB contributes 1.24 volts and the MSB 2.5 volts. If all the digital bits are set to logic 1 (+5 volts), then according to the Superposition Theorem, $V_{out} = 0.625 + 1.25 + 2.5 = 4.375$ volts. In other words, this D-A has a resolution of 0.625 volts and a range of 0 to 4.375 volts.

In general,

$$V_{out} = \frac{V_{logic}}{2}\left(N_2 + \frac{N_1}{2} + \frac{N_0}{4}\right) \tag{5.20}$$

where

V_{out}	is the output voltage of the D-A converter
V_{logic}	is the logic level into the D-A converter, 5 volts in this case
N_2, N_1 and N_0	are the MSB, NSB and LSB respectively of the binary number input to the D-A converter

Now we need to determine how many bits are required in the D-A converter for the pressure amplifier circuit.

D-A Converter Resolution

We can determine the required resolution of the D-A converter according to the following reasoning:

- The D-A will generate a signal V_{OS} that replaces the offset pot, which had a range of 0.75 volts to 1.65 volts.This is amplified by the offset gain K_{OS} (16.6 volts/volt) to shift the amplifier output signal V_{AD} up or down. The total range of shift is then $(1.65 - 0.75) \times 16.6 = 18.3$ volts. The step size of the D-A must be a small fraction of this 18.3 volts.
- The output swing of the amplifier worst case occurs for a maximum sensor gain K_T of 0.9mv/kPa. This is amplified by the forward gain of the amplifier K_A, 333. The output voltage swing for a full-scale change in air pressure ΔP_A of 10KPa is then

$$\begin{aligned} \Delta V_{AD} &= \Delta P_A \times K_T \times K_A \\ &= 10 \times 0.9 \times 10^{-3} \times 333 \\ &= 2.97\text{volts} \\ &\approx \pm 1.5\text{volts} \end{aligned}$$

- We would like to locate the output of the amplifier so that the signal never swings below 0.2 volts or above 4.7 volts. This allows a guard band of 0.75 volts above and below the output swing. We might somewhat arbitrarily choose to be able to place the offset signal with a resolution of half this, 0.375 volts.
- The required resolution of the D-A is in then the order of one part in $18.3/0.375 = 48.8$. The next larger binary number is $2^6 = 64$, so we require a 6 bit D-A converter.

This resolution is low enough that discrete 1% resistors (20KΩ and 10KΩ for example) may be used for the R-2R resistor ladder.

CMOS Output Specifications

The usual approach to D-A design is to have the logic signals switch an accurate, stable reference voltage. However, the accuracy required of this D-A converter (1 part in 64, 1.5%) may be low enough that a CMOS latch may be used to drive the ladder directly. This would greatly simplify the circuit design.

The output logic swing from CMOS logic (unlike the TTL family) is very nearly equal to the power supply levels: 0 and +5 volts in this case. The data dook for Texas Instruments 74HC logic ([**?**]) shows a typical output logic swing to within 1 millivolt of the supply levels. For the worst case, the output swing is still to within 10 millivolts of the supply levels. This suggests that the CMOS latch will drive the R-2R ladder with sufficient accuracy.

Furthermore, the output resistance of the logic, worst case, is given in the data book as 50Ω. If we use 10kΩ and 20kΩ as resistors in the R-2R ladder network, then the driving resistance of the logic device will be much lower than the resistance of the ladder network, so resistive loading will not be a problem.

Based on these specs, a CMOS latch such as the 74HC273 can drive the 6 bit ladder network directly.

D-A Amplifier

Analysing the output of a 6 bit D-A converter as we did in section **??** , using equation **??** on page **??** (modified for 6 bit input) we can determine that the output of the 6 bit D-A converter ranges from 0 to 4.92 volts in steps of 0.078 volts. The barometer interface circuit requires that the offset voltage V_{OS} vary between 0.75 volts to 1.65 volts, so amplification (actually, attenuation) and level shifting are required. The amplifier that provides this level shifting and attenuation also serves to buffer the internal resistance of the D-A from its load.

A non-inverting amplifier won't work, since the required gain is less than unity. The gain of an inverting amplifier may be set to anything from zero up[2], and the sign inversion introduced by the inverting amplifier may be taken care of in the software.

The transfer function of the amplifier circuit is shown in figure **??**, from which the slope **m** and offset **b** may be determined.

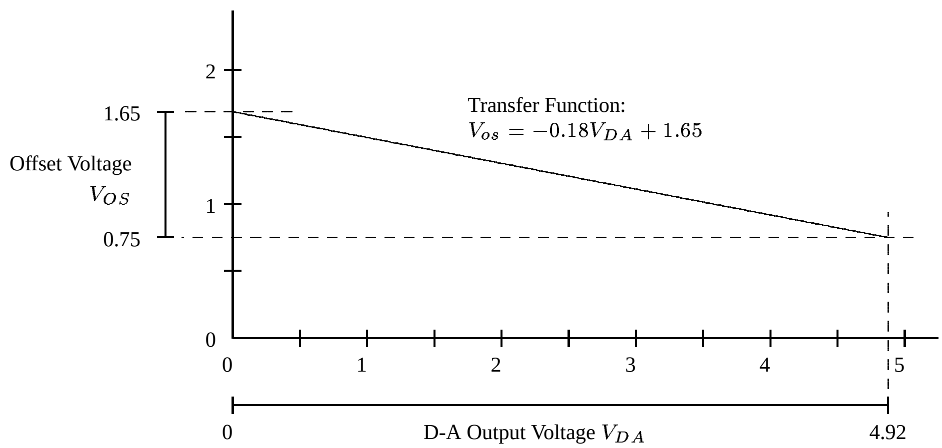


Figure 5.17: D-A Amplifier Transfer Function

The circuit of the amplifier is shown in figure **??**.

By comparison between the equation of the transfer function the equations for the amplifier, we have that

$$\frac{R_f}{R_i} = 0.18$$

[2]Well, actually, up to the open loop gain of the op-amp, to be precise.

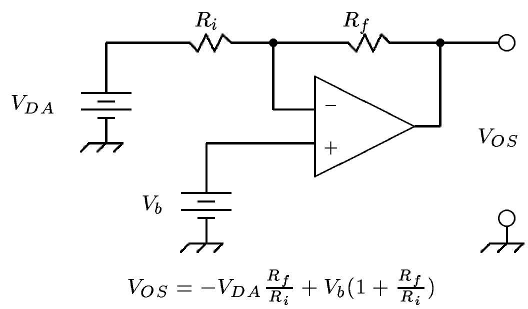
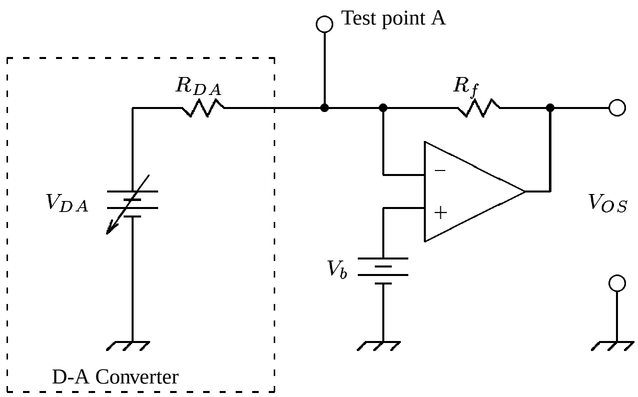


Figure 5.18: D-A Amplifier

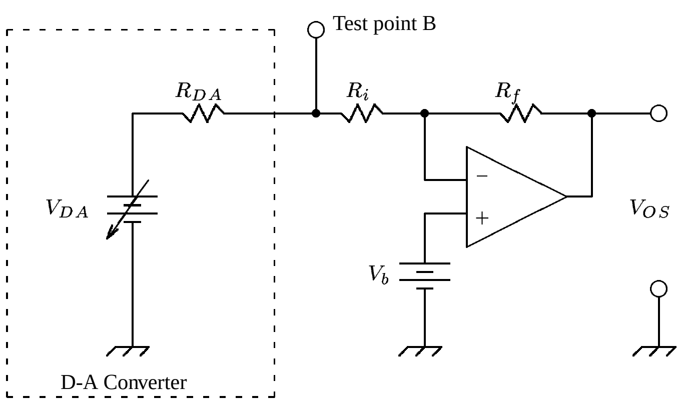
and

$$\begin{aligned} V_b &= 1.65/\left(1 + \frac{R_f}{R_i}\right) \\ &= 1.39 \text{ volts} \end{aligned}$$

Looking back into the D-A converter output, the load sees an internal D-A resistance R_{DA} of **R** ohms. This internal resistance could be used as R_i, (figure **??**A).



(a) D-A, Direct Connection to Amplifier



(b) D-A, With R_i

Figure 5.19: D-A Amplifier Connection

However, in this arrangement there is no voltage signal representing the D-A output voltage by itself: the test point **A** is a virtual earth. For troubleshooting purposes, it is better to provide an extra resistance and test point **B** (figure **??**B) where the output of the D-A can be measured. The voltage at **B** will be half the open circuit D-A voltage V_{DA}, but can be used to indicate that the D-A is operating correctly.

Automatic Calibration: Schematic

The complete schematic of the system, including a D-A converter for automatic calibration, is shown in figure **??**.

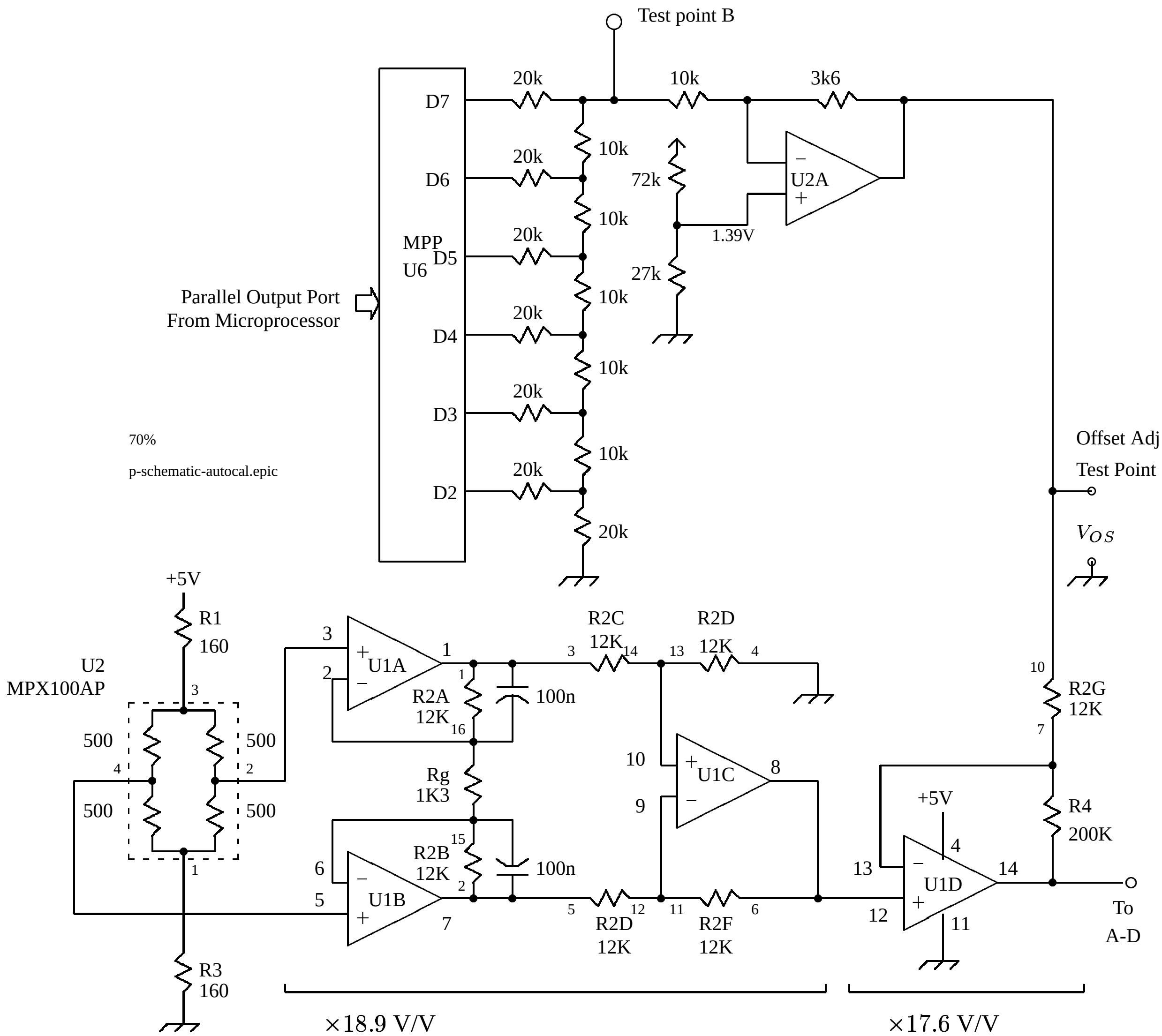


Figure 5.20: Barometric Pressure Interface, Automatic Calibration

Automatic Calibration: Algorithm

The microprocessor essentially mimics the manual calibration process of section **??** on page **??**. The only information it needs from the external world is the current value of atmospheric air pressure P_A.

1. When the microprocessor first reads the A-D input voltage V_{AD}, it will probably be near +5 volts or 0 volts. The processor then monitors that voltage while increasing the count into the D-A converter, which causes the offset voltage to ramp between its maximum and minimum values. At some point, the A-D input voltage should move to a value near the centre of the A-D input range. At this point, the micro freezes the value in the D-A register. Because it knows the constants relating D-A count and offset voltage, the micro now knows the value of the offset voltage V_{OS} that moves the interface into its linear region.

2. The micro uses the current value of air pressure P_A with the known values of amplifier gain K_A, offset gain K_{OS} and the offset voltage V_{OS} that it set in the previous step, in equation **??** (page **??**) to calculate the sensor gain K_T.

3. The micro now adjusts the D-A output so that the offset voltage V_{OS} is at such a value that an air pressure P_A of 100kPa would cause an A-D input voltage V_{AD} of 2.5 volts.

4. The micro stores the current values of the interface constants K_A, K_{OS}, V_{OS} and K_T in semi-permanent EEPROM memory. The interface is now calibrated and A-D readings can be used to calculate and display the current air pressure.

An assembly line production would use this process. An external control computer would download a calibration program and the current air pressure into the microprocessor. The calibration would take place without human intervention.

The calibration program should also have the capability for detecting that calibration did not occur properly. Then a failed production unit can be shunted into a reject bin for rework.

5.6 Reliability of the Design

Now that we have a circuit design, we must ensure that the circuit will work reliably, allowing for component tolerances and the effect of temperature induced drift of the components.

For example, the sensor constant can vary over a range of 2:1. Resistors have a tolerance of $\pm$5%. The operational amplifiers have offset voltages which can vary by $\pm$7mV. Can we be sure that the circuit will work when components of the tolerance extremes are used in the circuit?

The sensor has a temperature coefficient of -0.16% per degree C, the resistors change by 250ppm (parts per million) per degree C, and the amplifier offset voltages may change by as much as $\pm 30\mu$volts per degree C. What effect will these drifts have on the operation of the barometer, bearing in mind that the circuit is not supposed to act as a thermometer?

We can and should build and test one or more prototypes. However, the correct functioning of a prototype is a necessary but not sufficient condition to determine a reliable design. The fact that a prototype works merely means that at least one version of the circuit will function. It's no guarantee that all circuits will function.

To ensure the reliable operation of the circuit, the correct strategy is to perform an engineering analysis, checking circuit operation by calculation and simulation. This will provide the necessary confidence to build the circuit in quantity, and be assured that it will function under all specified conditions. Where possible, to ensure that some massive blunder has not occurred, the calculations should be checked against the prototype. If the calculations and simulation accurately predict the behaviour of the prototype, then we can have some confidence in the predictions.

5.6.1 Circuit Tolerance Analysis

The tolerances of the circuit components raise two concerns:

- Will the circuit function, or will some voltage or current run into saturation or cutoff?
- Can the circuit calibration procedure compensate for circuit tolerances, or do we lose measurement accuracy under some conditions?

This is potentially an unweildy problem, because of the combinatorial explosion of tolerance variables. The parameters and equations of a spreadsheet model for the manual offset adjustment version of the interface are shown in figure **??**. A typical spreadsheet printout is shown in figure **??**.

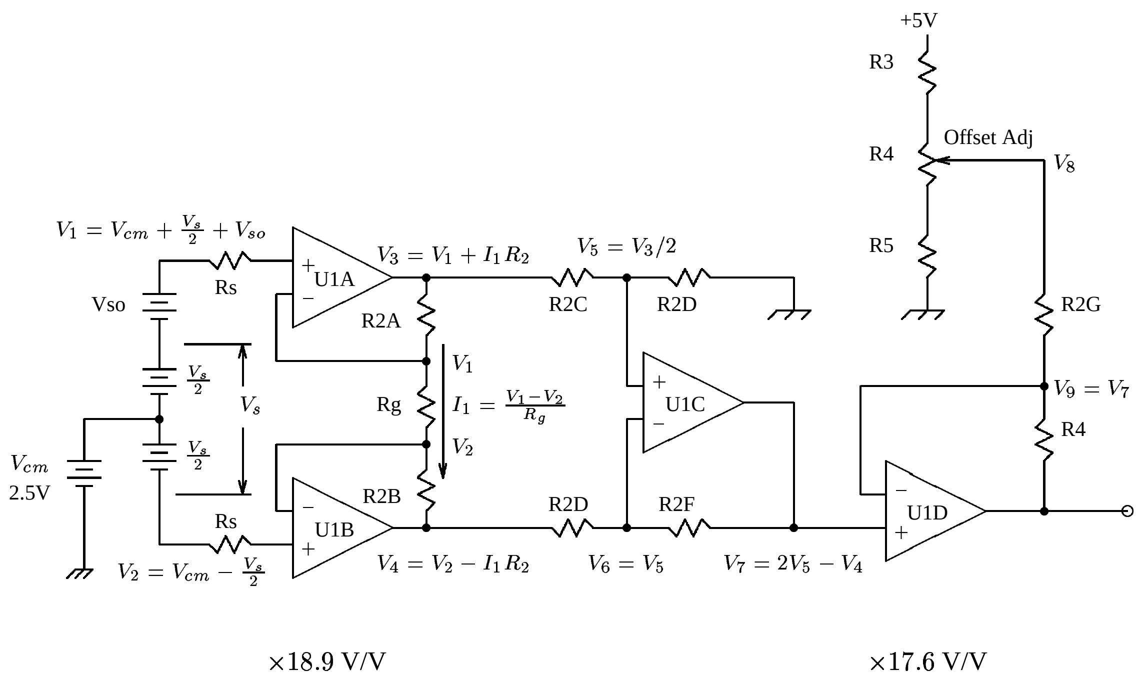


Figure 5.21: Circuit Equations

The tinkering with spreadsheet model turned up the following results:

- The sensor offset V_{so} does not cause the amplifier to saturate but does have a dramatic effect on the output voltage V_{AD}. (Notice that sensor offset V_{so} is a property of the sensor: do not confuse it with the offset voltage V_{OS} of the interface.)

Sensor Constant	K_T	(data)	0.6×10^{-3}	V/kPa
Air Pressure	P_A	(data)	100	kPa
Sensor Offset	V_{so}	(data)	10×10^{-3}	V
Gain Resistor	R_g	(data)	1300	Ω
Resistor	R_2	(data)	12000	Ω
Sensor Output	V_s	$K_T P_A$	0.06	V
	V_1	$V_{cm} + \frac{V_s}{2} + V_{so}$	2.53	V
	V_2	$V_{cm} - \frac{V_s}{2}$	2.47	V
	I_1	$(V_1 - V_2)/R_g$	48	μAmp
	V_3	$V_1 + R_2 I_1$	3.084	V
	V_4	$V_1 - R_2 I_1$	1.916	V
	V_5	$V_3/2$	1.542	V
	V_6	V_5	1.524	V
	V_7	$2V_5 - V_4$	1.167	V
K_{os}	V_8	(data)	1.68	V
	V_9	V_7	1.167	V
Resistor	R_4	(data)	200000	Ω
Output Voltage	V_{AD}	$V_7(1 + \frac{R_4}{R_2}) - V_8 \frac{R_4}{R_2}$	2.00	V
A/D Reading	N_{AD}	$\frac{V_{AD}}{5} 256$	102	counts

Figure 5.22: Amplifier Spreadsheet Model and Results

- The offset voltage V_{OS} may be adjusted to compensate for the effect of sensor offset voltage, but a larger range of offset is required than that originally anticipated. The output voltage V_{AD} is very sensitive to the setting of V_{OS}, so the pot R_4 should be a multi-turn unit.
- A combination of large offset and high sensor gain K_T cause V_3, the output of U1A, to exceed 3.5 volts. This is the maximum output of the LM324 operational amplifier, and so an LMC660 is required.
- For low sensor gain, the change in A-D reading over the full range of air pressures (95 to 105 kPa) is over 60 counts, so the resolution is satisfactory even for low sensor gain.

These results could have been predicted from an analysis of the circuit, but the spreadsheet model makes it easy to explore the effect of a variety of options and combinations of parameters.

A circuit simulation program such as SPICE could also be used to analyse the circuit, and is a better choice where an accurate op-amp model is required. The spreadsheet model assumes ideal op amps. On the other hand, spreadsheet programs are readily available and easy to use.

5.6.2 Temperature Drift

In every engineering project, there is at least one killer problem which determines success or failure. It's important to identify the killer problem as early as possible. In this system, the killer problem is temperature drift.

There are three evident sources of temperature drift:

Pressure Sensor Drift An analysis of the pressure sensor temperature drift [**?**] in the circuit of figure **??** shows two competing effects: the gain of the sensor decreases with temperature, but this is partially compensated by in increase in bridge resistance. The net result is a coefficient of -0.16% per degree C.

The effect on the output is a change of A-D reading of about 1.6 counts/^{o}C. Over a $\pm 10^o$C temperature range, this is an error of 16 counts out of a total of 100, or a 16% error: not very acceptable. Fortunately, since it is a predictable effect, it may be compensated for by measuring the ambient temperature and modifying the sensor constant.

Offset voltage drift For the LMC660, the typical figure for offset voltage drift is given as 1.3μvolts per degree C. The spreadsheet model (or an algebraic analysis) turn up the result that this causes a drift of about 0.5 mv/^{o}C, much less than one count of the A-D converter. This can therefore be neglected.

Resistor temperature coefficients Most of the resistors (R2A through R2H) are on the same package and so can be expected to track in temperature. As well, the two amplifier gains are the result of ratios of resistance (equations **??** and **??**), so the temperature coefficients may be expected to cancel. Simulation of resistor drift with the spreadsheet confirms this: the effects of resistor drift are small enough to be neglected.