AN1517

# Pressure Switch Design with Semiconductor Pressure Sensors

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## INTRODUCTION

The Pressure Switch concept is simple, as are the additions to conventional signal conditioning circuitry required to provide a pressure threshold (or thresholds) at which the output switches logic state. This logic–level output may be input to a microcontroller, drive an LED, control an electronic switch, etc. The user–programmed threshold (or reference voltage) determines the pressure at which the output state will switch. An additional feature of this minimal component design is an optional user–defined hysteresis setting that will eliminate multiple output transitions when the pressure sensor voltage is comparable to the threshold voltage.

This paper presents the characteristics and design criteria for each of the major subsystems of the pressure switch design: the pressure sensor, the signal conditioning (gain) stage, and the comparator output stage. Additionally, an entire section will be devoted to comparator circuit topologies which employ comparator ICs and/or operational amplifiers. A window comparator design (high and low thresholds) is also included. This section will discuss the characteristics and design criteria for each comparator circuit, while evaluating them in overall performance (i.e., switching speed, logic–level voltages, etc.).

## BASIC SENSOR OPERATION

Motorola's MPX2000 Series sensors are temperature compensated and calibrated (i.e., offset and full–scale span are precision trimmed) pressure transducers. These sensors are available in full–scale pressure ranges from 10 kPa (1.5 psi) to 200 kPa (30 psi). Although the specifications (see Table 1) in the data sheets apply only to a 10 V supply voltage, the output of these devices is ratiometric with the supply voltage. For example, at the absolute maximum supply voltage rating, 16 V, the sensor will produce a differential output voltage of 64 mV at the rated full–scale pressure of the given sensor. One exception to this is that the full–scale span of the MPX2010 (10 kPa sensor) will be only 40 mV due to the device's slightly lower sensitivity. Since the maximum supply voltage produces the most output voltage, it is evident that even the best case scenario will require some signal conditioning to obtain a usable voltage level. For this specific design, an MPX2100 and 5.0 V supply is used to provide a maximum sensor output of 20 mV. The sensor output is then signal conditioned to obtain a four volt signal swing (span).

**Table 1. MPX2100 Electrical Characteristics for $V_S$ = 10 V, $T_A$ = 25°C**

| Characteristic | Symbol | Minimum | Typical | Max | Unit |
|---|---|---|---|---|---|
| Pressure Range | $P_{OP}$ | 0 | | 100 | kPa |
| Supply Voltage | $V_S$ | | 10 | 16 | Vdc |
| Full Scale Span | $V_{FSS}$ | 38.5 | 40 | 41.5 | mV |
| Zero Pressure Offset | $V_{off}$ | | 0.05 | 0.1 | mV |
| Sensitivity | S | | 0.4 | | mV/kPa |
| Linearity | | | 0.05 | | %FSS |
| Temperature Effect on Span | | | 0.5 | | %FSS |
| Temperature Effect on Offset | | | 0.2 | | %FSS |

## THE SIGNAL CONDITIONING

The amplifier circuitry, shown in Figure 1, is composed of two op–amps. This interface circuit has a much lower component count than conventional quad op amp instrumentation amplifiers. The two op amp design offers the high input impedance, low output impedance, and high gain desired for a transducer interface, while performing a differential to single–ended conversion. The gain is set by the following equation:

$$\text{GAIN} = 1 + \frac{R6}{R5}$$

where R6 = R3 and R4 = R5.

For this specific design, the gain is set to 201 by setting R6 = 20 kΩ and R5 = 100 Ω. Using these values and setting R6 = R3 and R4 = R5 gives the desired gain without loading the reference voltage divider formed by R1 and $R_{off}$. The offset voltage is set via this voltage divider by choosing the value of $R_{off}$. This enables the user to adjust the offset for each application's requirements.

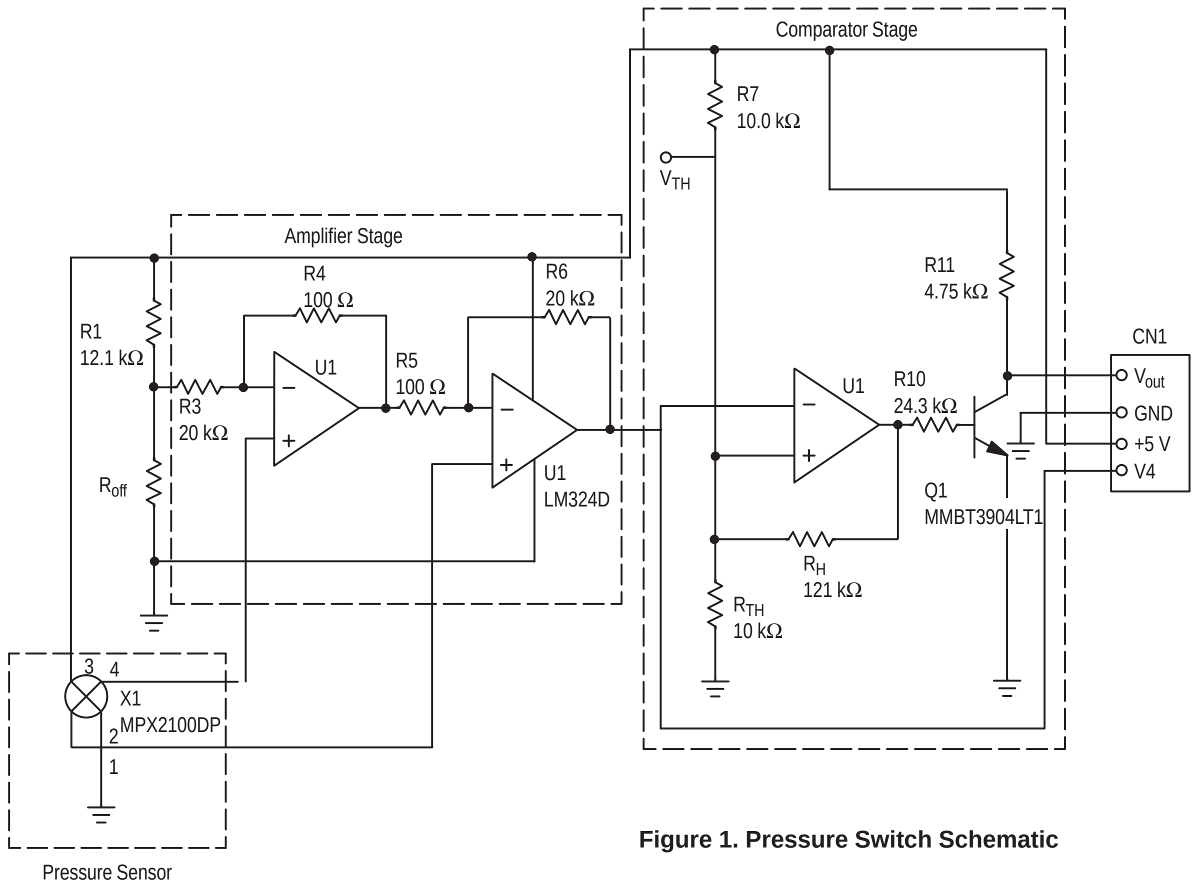


**Figure 1. Pressure Switch Schematic**

## THE COMPARISON STAGE

The comparison stage is the "heart" of the pressure switch design. This stage converts the analog voltage output to a digital output, as dictated by the comparator's threshold. The comparison stage has a few design issues which must be addressed:

- The threshold for which the output switches must be programmable. The threshold is easily set by dividing the supply voltage with resistors R7 and $R_{TH}$. In Figure 1, the threshold is set at 2.5 V for R7 = $R_{TH}$ = 10 kΩ.
- A method for providing an appropriate amount of hysteresis should be available. Hysteresis prevents multiple transitions from occurring when slow varying signal inputs oscillate about the threshold. The hysteresis can be set by applying positive feedback. The amount of hysteresis is determined by the value of the feedback resistor, $R_H$ (refer to equations in the following section).
- It is ideal for the comparator's logic level output to swing from one supply rail to the other. In practice, this is not possible. Thus, the goal is to swing as high and low as possible for a given set of supplies. This offers the greatest difference between logic states and will avoid having a microcontroller read the switch level as being in an indeterminate state.
- In order to be compatible with CMOS circuitry and to avoid microcontroller timing delay errors, the comparator must switch sufficiently fast.
- By using two comparators, a window comparator may be implemented. The window comparator may be used to monitor when the applied pressure is within a set range. By adjusting the input thresholds, the window width can be customized for a given application. As with the single

threshold design, positive feedback can be used to provide hysteresis for both switching points. The window comparator and the other comparator circuits will be explained in the following section.

## EXAMPLE COMPARATOR CIRCUITS

Several comparator circuits were built and evaluated. Comparator stages using the LM311 comparator, LM358 Op–Amp (with and without an output transistor stage), and LM339 were examined. Each comparator was evaluated on output voltage levels (dynamic range), transition speed, and the relative component count required for the complete pressure switch design. This comparison is tabulated in Table 2**.**

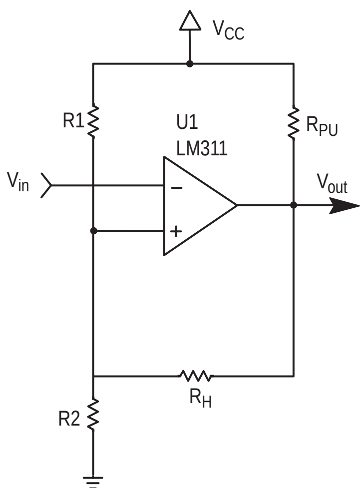


**Figure 2. LM311 Comparator Circuit Schematic**

### LM311 Used in a Comparator Circuit

The LM311 chip is designed specifically for use as a comparator and thus has short delay times, high slew rate, and an open collector output. A pull–up resistor at the output is all that is needed to obtain a rail–to–rail output. Additionally, the LM311 is a reverse logic circuit; that is, for an input lower than the reference voltage, the output is high. Likewise, when the input voltage is higher than the reference voltage, the output is low. Figure 2 shows a schematic of the LM311 stage with threshold setting resistor divider, hysteresis resistor, and the open–collector pull–up resistor. Table 2 shows the comparator's performance. Based on its performance, this circuit can be used in many types of applications, including interface to microprocessors.

The amount of hysteresis can be calculated by the following equations:

$$V_{REF} = \frac{R2}{R1 + R2} V_{CC},$$

neglecting the effect of $R_H$.

$$V_{REFH} = \frac{R1R2 + R2R_H}{R1R2 + R1R_H + R2R_H} V_{CC}$$

$$V_{REFL} = \frac{R2R_H}{R1R2 + R1R_H + R2R_H} V_{CC}$$

$$HYSTERESIS = V_{REF} - V_{REFL}$$

when the normal state is below $V_{REF}$, or

$$HYSTERESIS = V_{REFH} - V_{REF}$$

when the normal state is above $V_{REF}$.

**Table 2. Comparator Circuits Performance Characteristics**

| Characteristic | LM311 | LM358 | LM358 w/ Trans. | Unit |
|---|---|---|---|---|
| Switching Speeds | | | | |
| Rise Time | 1.40 | 5.58 | 2.20 | µs |
| Fall Time | 0.04 | 6.28 | 1.30 | µs |
| Output Levels | | | | |
| $V_{OH}$ | 4.91 | 3.64 | 5.00 | V |
| $V_{OL}$ | 61.1 | 38.0 | 66.0 | mV |
| Circuit Logic Type | NEGATIVE | NEGATIVE | POSITIVE | |

The initial calculation for $V_{REF}$ will be slightly in error due to neglecting the effect of $R_H$. To establish a precise value for $V_{REF}$ (including $R_H$ in the circuit), recompute R1 taking into account that $V_{REF}$ depends on R1, R2, and $R_H$. It turns out that when the normal state is below $V_{REF}$, $R_H$ is in parallel with R1:

$$V_{REF} = \frac{R2}{R1 \parallel R_H + R2} V_{CC}$$

(which is identical to the equation for $V_{REFH}$)

Alternately, when the normal state is above $V_{REF}$, $R_H$ is in parallel with R2:

$$V_{REF} = \frac{R2 \parallel R_H}{R1 + R2 \parallel R_H} V_{CC}$$

(which is identical to the equation for $V_{REFL}$)

These two additional equations for $V_{REF}$ can be used to calculate a more precise value for $V_{REF}$.

The user should be aware that $V_{REF}$, $V_{REFH}$ and $V_{REFL}$ are chosen for each application, depending on the desired switching point and hysteresis values. Also, the user must specify which range (either above or below the reference voltage) is the desired normal state (see Figure 3). Referring to Figure 3, if the normal state is below the reference voltage then $V_{REFL}$ ($V_{REFH}$ is only used to calculate a more precise value for $V_{REF}$ as explained above) is below $V_{REF}$ by the desired amount of hysteresis (use $V_{REFL}$ to calculate $R_H$). Alternately, if the normal state is above the reference voltage then $V_{REFH}$ ($V_{REFL}$ is only used to calculate a more precise value for $V_{REF}$) is above $V_{REF}$ by the desired amount of hysteresis (use $V_{REFH}$ to calculate $R_H$).

An illustration of hysteresis and the relationship between these voltages is shown in Figure 3.

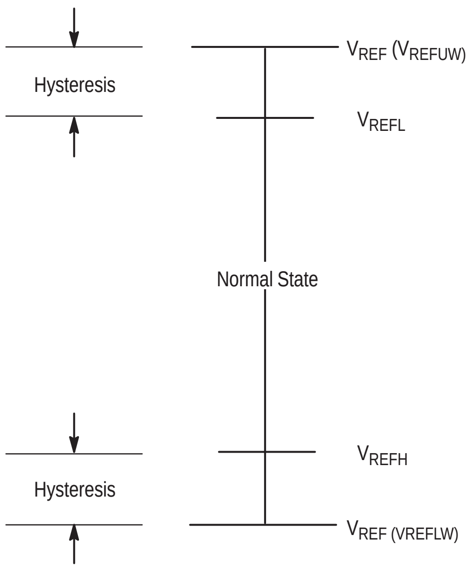


**Figure 3. Setting the Reference Voltages**

## LM358 Op Amp Used in a Comparator Circuit

Figure 4 shows the schematic for the LM358 op amp comparator stage, and Table 2 shows its performance. Since the LM358 is an operational amplifier, it does not have the fast slew–rate of a comparator IC nor the open collector output. Comparing the LM358 and the LM311 (Table 2), the LM311 is better for logic/switching applications since its output nearly extends from rail to rail and has a sufficiently high switching speed. The LM358 will perform well in applications where the switching speed and logic–state levels are not critical (LED output, etc.). The design of the LM358 comparator is accomplished by using the same equations and procedure presented for the LM311. This circuit is also reverse logic.

## LM358 Op Amp with a Transistor Output Stage Used in a Comparator Circuit

The LM358 with a transistor output stage is shown in Figure 5. This circuit has similar performance to the LM311 comparator: its output reaches the upper rail and its switching speed is comparable to the LM311's. This enhanced performance does, however, require an additional transistor and base resistor. Referring to Figure 1, note that this comparator topology was chosen for the pressure switch design. The LM324 is a quad op amp that has equivalent amplifier characteristics to the LM358.

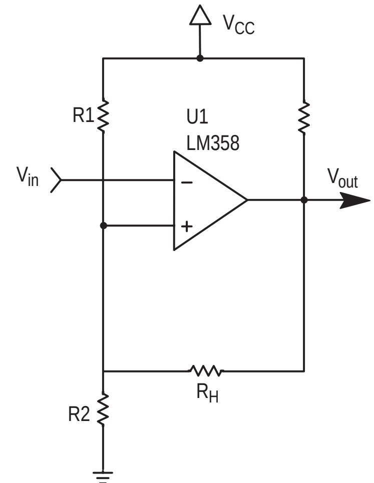


**Figure 4. LM358 Comparator Circuit Schematic**

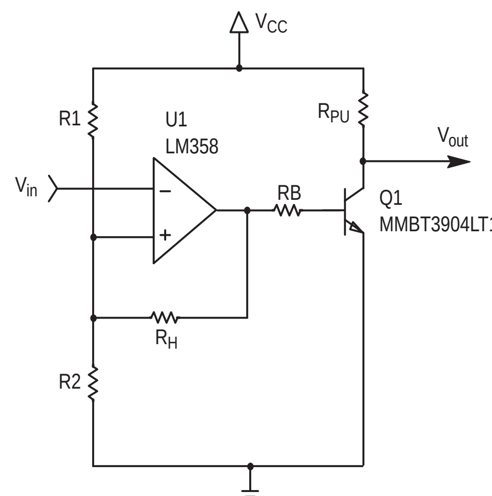


**Figure 5. LM358 with a Transistor Output Stage Comparator Circuit Schematic**

Like the other two circuits, this comparator circuit can be designed with the same equations and procedure. The values for $R_B$ and $R_{PU}$ are chosen to give a 5:1 ratio in Q1's collector current to its base current, in order to insure that Q1 is well–saturated ($V_{out}$ can pull down very close to ground when Q1 is on). Once the 5:1 ratio is chosen, the actual resistance values determine the desired switching speed for turning Q1 on and off. Also, $R_{PU}$ limits the collector current to be within the maximum specification for the given transistor (see example values in Figure 1). Unlike the other two circuits, this circuit is positive logic due to the additional inversion created at the output transistor stage.

## LM339 Used in a Window Comparator Circuit

Using two voltage references to detect when the input is within a certain range is another possibility for the pressure switch design. The window comparator's schematic is shown in Figure 6. The LM339 is a quad comparator IC (it has open collector outputs), and its performance will be similar to that of the LM311.

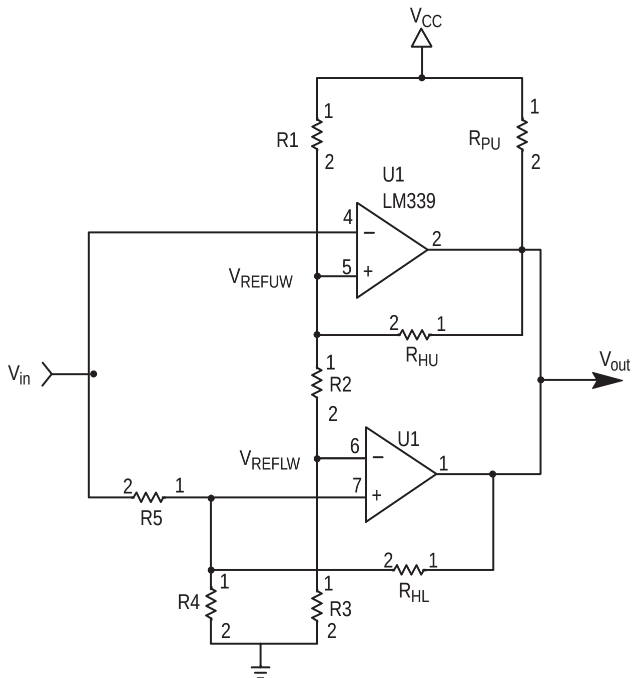


**Figure 6. LM339 Window Comparator Circuit Schematic**

Obtaining the correct amount of hysteresis and the input reference voltages is slightly different than with the other circuits. The following equations are used to calculate the hysteresis and reference voltages. Referring to Figure 3, $V_{REFUW}$ is the upper window reference voltage and $V_{REFLW}$ is the lower window reference voltage. Remember that reference voltage and threshold voltage are interchangeable terms.

For the upper window threshold:

Choose the value for $V_{REFUW}$ and R1 (e.g., 10 kΩ). Then, by voltage division, calculate the total resistance of the combination of R2 and R3 (named R23 for identification) to obtain the desired value for $V_{REFUW}$, neglecting the effect of $R_{HU}$:

$$V_{REFUW} = \frac{R23}{R1 + R23} V_{CC}$$

The amount of hysteresis can be calculated by the following equation:

$$V_{REFL} = \frac{R23R_{HU}}{R1R23 + R1R_{HU} + R23R_{HU}} V_{CC}$$

Notice that the upper window reference voltage, $V_{REFUW}$, is now equal to its $V_{REFL}$ value, since at this moment, the input voltage is above the normal state.

$$\text{HYSTERESIS} = V_{REFUW} - V_{REFL},$$

where VREFL is chosen to give the desired amount of hysteresis for the application.

The initial calculation for $V_{REFUW}$ will be slightly in error due to neglecting the effect of $R_{HU}$. To establish a precise value for $V_{REFUW}$ (including $R_{HU}$ in the circuit), recompute R1 taking into account that $V_{REFUW}$ depends on R2 and R3 and the parallel combination of R1 and $R_{HU}$. This more precise value is calculated with the following equation:

$$V_{REFUW} = \frac{R23}{R1 \parallel R_{HU} + R23} V_{CC}$$

for the lower window threshold choose the value for $V_{REFLW}$.

$$\text{Set } V_{REFLW} = \frac{R3}{R1 \parallel R_{HU} + R2 + R3} V_{CC},$$

where R2 + R3 = R23 from above calculation.

To calculate the hysteresis resistor:

The input to the lower comparator is one half $V_{in}$ (since R4 = R5) when in the normal state. When $V_{REFLW}$ is above one half of $V_{in}$ (i.e., the input voltage has fallen below the window), $R_{HL}$ parallels R4, thus loading down $V_{in}$. The resulting input to the comparator can be referred to as $V_{INL}$ (a lower input voltage). To summarize, when the input is within the window, the output is high and only R4 is connected to ground from the comparator's positive terminal. This establishes one half of $V_{in}$ to be compared with $V_{REFLW}$. When the input voltage is below $V_{REFLW}$, the output is low, and $R_{HL}$ is effectively in parallel with R4. By voltage division, less of the input voltage will fall across the parallel combination of R4 and $R_{HL}$, demanding that a higher input voltage at $V_{in}$ be required to make the noninverting input exceed $V_{REFLW}$.

Therefore the following equations are established:

$$\text{HYSTERESIS} = V_{REFLW} - V_{INL}$$

Choose R4 = R5 to simplify the design.

$$R_{HL} = \frac{R4R5\left(V_{REFLW} - V_{INL} - V_{CC}\right)}{(R4 + R5)\left(V_{INL} - V_{REFLW}\right)}$$

**IMPORTANT NOTE:**

As explained above, because the input voltage is divided in half by R4 and R5, all calculations are done relative to the one half value of $V_{in}$. Therefore, for a hysteresis of 200 mV (relative to $V_{in}$), the above equations must use one half this hysteresis value (100 mV). Also, if a $V_{REFLW}$ value of 2.0 V is desired (relative to $V_{in}$), then 1.0 V for its value should be used in the above equations. The value for $V_{INL}$ should be scaled by one half also.

The window comparator design can also be designed using operational amplifiers and the same equations as for the LM339 comparator circuit. For the best performance, however, a transistor output stage should be included in the design.

## TEST/CALIBRATION PROCEDURE

1. Before testing the circuit, the user–defined values for $R_{TH}$, $R_H$ and $R_{off}$ should be calculated for the desired application.

The sensor offset voltage is set by

$$V_{off} = \frac{V_{off}}{R1 + R_{off}} \; V_{CC} .$$

Then, the amplified sensor voltage corresponding to a given pressure is calculated by

$V_{sensor}$ = 201 x 0.0002 x APPLIED PRESSURE + $V_{off}$,

where 201 is the gain, 0.0002 is in units of V/kPa and APPLIED PRESSURE is in kPa.

The threshold voltage, $V_{TH}$, at which the output changes state is calculated by determining $V_{sensor}$ at the pressure that causes this change of state:

$V_{TH}$ = $V_{sensor}$ (@ pressure threshold) =

$$\frac{R_{TH}}{R7 + R_{TH}} \; V_{CC} .$$

If hysteresis is desired, refer to the LM311 Used in a Comparator section to determine $R_H$.

2. To test this design, connect a +5 volt supply between pins 3 and 4 of the connector CN1.
3. Connect a volt meter to pins 1 and 4 of CN1 to measure the output voltage and amplified sensor voltage, respectively.
4. Connect an additional volt meter to the $V_{TH}$ probe point to verify the threshold voltage.
5. Turn on the supply voltage.
6. With no pressure applied, check to see that $V_{off}$ is correct by measuring the voltage at the output of the gain stage (the volt meter connected to Pin 4 of CN1). If desired, $V_{off}$ can be fine tuned by using a potentiometer for $R_{off}$.
7. Check to see that the volt meter monitoring $V_{TH}$ displays the desired voltage for the output to change states. Use a potentiometer for $R_{TH}$ to fine tune $V_{TH}$, if desired.
8. Apply pressure to the sensor. Monitor the sensor's output via the volt meter connected to pin 4 of CN1. The output will switch from low to high when this pressure sensor voltage reaches or exceeds the threshold voltage.
9. If hysteresis is used, with the output high (pressure sensor voltage greater than the threshold voltage), check to see if $V_{TH}$ has dropped by the amount of hysteresis desired.

   A potentiometer can be used for $R_H$ to fine tune the amount of hysteresis.

## CONCLUSION

The pressure switch design uses a comparator to create a logic level output by comparing the pressure sensor output voltage and a user–defined reference voltage. The flexibility of this minimal component, high performance design makes it compatible with many different applications. The design presented here uses an op amp with a transistor output stage, yielding excellent logic–level outputs and output transition speeds for many applications. Finally, several other comparison stage designs, including a window comparator, are evaluated and compared for overall performance.

# NOTES

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