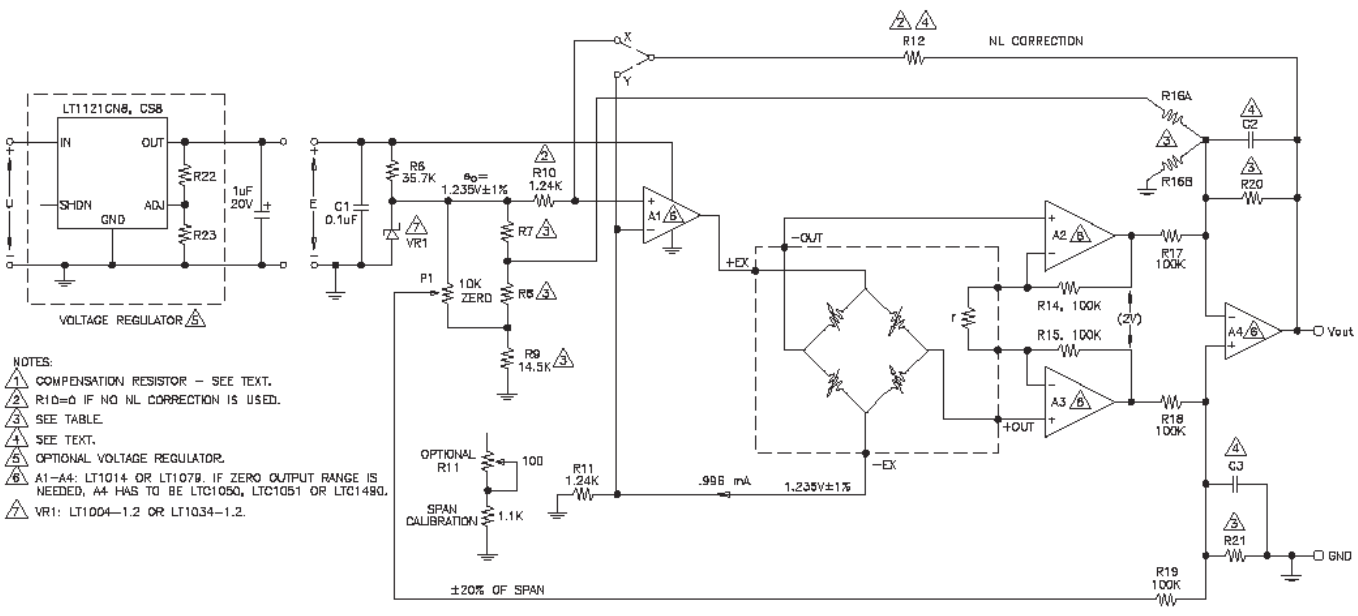
Signal Conditioning Circuit, Popular Outputs using On Board Gain Adjust Circuitry (AN-001)

INTRODUCTION

Piezoresistive pressure sensors produce an analog voltage output that varies proportionally with applied pressure. For most integrated sensor designs, the typical full-scale output span is approximately 100 mV. While this is adequate for many signal processing environments, certain applications require higher-level output signals—such as a 0–5 V span—which necessitate additional signal conditioning, including gain stages and voltage translation.

A well-designed signal conditioning circuit for pressure sensors should perform several critical functions: zero offset (null) adjustment, span (gain) calibration, and temperature compensation of both zero and span. Additionally, it must provide accurate signal amplification and power regulation. In more demanding applications, active nonlinearity correction and frequency response tailoring may also be required to achieve optimal sensor accuracy and stability.

This application note details a practical analog signal conditioning circuit designed for temperature-compensated piezoresistive pressure sensors (see Figure 1). The circuit architecture allows for precise, non-interacting zero and span calibration using a single power supply. It supports both three-wire voltage output and two-wire current loop output configurations. The design is compatible with AVSensors' compensated pressure sensor series utilizing constant current excitation (e.g., CTO Series, CHT-Series, MIOF-xxx CC Series). Several output signal formats are demonstrated, including a “live-zero” output at 1 V, which provides a built-in failure detection mechanism—distinguishing between a true zero-pressure condition and sensor disconnection or failure.



OUTPUT RANGE	R7	R8	R9	R16A	R16B	R20	R21	R22	R23	E_{MIN}	U_{MIN}
1 TO 5V	——	——	4.75K	——	100K	200K	200K	18K	13K	8.9V	10V
1 TO 6V	——	——	4.75K	——	100K	250K	250K	18K	13K	8.9V	10V
0 TO 5V	4.99K	4.99K	3.01K	100K	——	250K	250K	18K	13K	8.9V	10V
0 TO 10V	4.99K	4.99K	3.01K	100K	——	500K	500K	22K	12K	10.1V	11V

Figure 1 - Transducer Circuit - Voltage Output

The sensor assembly includes a temperature-compensated silicon pressure sensor paired with a precision gain-set resistor (R). This resistor is selected to normalize the output span of the recommended external amplifier, enabling consistent full-scale output across sensors. As a result, the system functions as a cost-effective, interchangeable high-level transducer, ideal for volume production and field replacement scenarios.

To determine whether a specific AVSensors model is uncompensated, passively compensated, or fully compensated with an integrated gain-set resistor, consult the corresponding product datasheet. For further information on passive temperature compensation strategies or sensor interchangeability principles, refer to the relevant AVSensors Applicaton Notes.

CONSTANT CURRENT SOURCE

The most straightforward implementation of sensor temperature compensation utilizes constant current excitation, configured around operational amplifier A1, as illustrated in Figure 1. In this setup, the pressure sensor is placed within the feedback loop of A1, forming a controlled current source. The loop current is determined by the reference voltage e_0 and the precision resistor R11, excluding any effects from the optional nonlinearity correction loop:

$$I = e_o/R_{11}$$

The compliance voltage of this current source is constrained by the supply rail, the output swing limitations of amplifier A1, and the voltage drop across R11. To ensure proper operation under all conditions, the required compliance voltage should be calculated using worst-case assumptions—for instance, a maximum bridge resistance of 6.0 kΩ at 25°C with a temperature coefficient of resistance (TCR) of +0.22%/°C, based on the sensor's compensation characteristics.

A stable reference voltage is generated using a temperature-compensated bandgap reference diode (VR1). This voltage serves a dual role: it establishes the excitation current for the sensor and acts as the live-zero reference level for output configurations such as 1–5 V or 1–6 V. Additionally, it provides a stable bias across potentiometer P1 for precise zero offset trimming.

DIFFERENTIAL NORMALIZING AMPLIFIER

Zero and span temperature compensation for the sensor is characterized under no-load output conditions. Because the sensor's bridge resistance varies with temperature, any significant input loading from the amplifier can introduce additional temperature-dependent error. To mitigate this, a differential normalizing amplifier configuration is employed. This topology offers a very high input impedance and excellent common-mode rejection, which remains largely unaffected by component tolerances—ensuring accurate and stable signal processing.

The output voltage swing of this amplifier stage is ultimately constrained by the input common-mode voltage range. With zero differential input, the output of amplifier A2 rests at the bridge's common-mode level and can only decrease to the system ground. Under worst-case conditions—assuming a 1.0 mA excitation current—the common-mode voltage may reach approximately 2.3 V, limiting the maximum achievable differential output swing to around 4.6 V.

In the reference circuit, a 2.0 V output span was selected to ensure linearity and headroom. The amplifier gain is adjustable to accommodate sensor spans from 33 mV to 115 mV at 1.0 mA excitation, which corresponds to spans from 50 mV to 170 mV at 1.5 mA. The required gain, denoted as K_1, is calculated using the following expression:

$$K_1 = 1 + (R_{14} + R_{15})/(R_{13} + P_2)$$

These equations ensure symmetrical gain control while preventing the adjustment potentiometer from introducing instability or exceeding the intended gain limits.

$$R_{13} = P\,(G_1 - 1)(G_2 - G_1)$$

$$R_{14} = P\,(G_1 - 1)(G_2 - 1)/2(G_2 - G_1)$$

Common-mode rejection (CMR) is a critical parameter for this amplifier stage. As the bridge resistance changes with temperature—approximately +0.22%/°C for temperature-compensated sensors and up to +0.27%/°C for uncompensated types—the bridge voltage will vary accordingly under constant current excitation. Over a 100°C operating range, this translates to a common-mode voltage shift of approximately 0.66 V for compensated sensors.

Assuming a worst-case differential CMR of 90 dB for this amplifier stage (e.g., when using an LT1014 op-amp), this variation in common-mode voltage would induce a negligible zero shift—approximately 0.042% over 100°C—based on a 50 mV sensor span. This level of thermal sensitivity is acceptable for most precision applications.

TRANSDUCER CIRCUIT

The differential input offset drift of amplifiers A2 and A3 introduces temperature-dependent zero shift in the transducer output. For instance, the LT1014 operational amplifier exhibits a worst-case offset drift of 5 µV/°C. When used with a sensor span as low as 50 mV, this drift can contribute up to 1% zero error over a 100°C temperature range. Such error must be considered in applications with tight accuracy requirements.

SECOND STAGE AMPLIFIER

The fixed gain output amplifier has two differential inputs. The first input (R17, R18) processes the output from the normalizing amplifier. The other input (R16, R19) is used to generate a zero bias level for the output options with live zero and provides fine zeroing adjustment of ±20% of the sensor span. Since zeroing is done in the first stage, the change of zero does not affect span.

The gain K2 of the second stage is set by:

The fixed-gain output amplifier (Stage 2) features two differential input paths. The primary input, composed of resistors R17 and R18, receives the amplified signal from the normalizing stage. The secondary input path (R16 and R19) sets a baseline zero-bias voltage for live-zero output configurations (e.g., 1–5 V), and allows fine zero adjustment—typically ±20% of full-scale span. Because coarse zeroing is performed in the first stage, zero adjustment here does not influence the span.

The gain K_2 of this second stage is defined by matched resistor pairs:

$$K_2 = R_{20} / R_{17} = R_{21} / R_{18}$$

Common-mode rejection in this stage is even more critical than in the first. The input to the R17/R18 leg may experience a worst-case common-mode shift of up to 0.66 V over a 100°C temperature range, due to bridge resistance variation under constant current excitation. If the gain-setting feedback resistors have a tolerance of ±1%, the expected common-mode rejection ratio (CMRR) drops to approximately 28 dB. This can result in a worst-case zero drift of about 1.3% over 100°C. However, with tighter resistor matching, this error is significantly reduced; typical zero drift values are two to four times better than the worst-case scenario.

Offset voltage temperature drift in this stage is not a critical factor. For instance, with a drift of 5 µV/°C over a 100°C range, the corresponding zero shift in the output is only 0.025% of full-scale for a 2 V input span. This minimal influence makes the amplifier suitable for most high-precision applications where stability across temperature is required.

NONLINEARITY CORRECTION

An optional nonlinearity correction loop can be introduced using resistor R12. This loop feeds a portion of the output voltage back into the sensor excitation circuit, modulating the bridge supply voltage to inject a second-order pressure-dependent component into the signal. This compensation technique effectively corrects inherent sensor nonlinearity.

For sensors exhibiting positive nonlinearity, feedback is applied to the non-inverting input (X) of amplifier A1. For negative nonlinearity, the feedback is applied to the inverting input (Y). The polarity of this connection determines the curvature of the correction.

The appropriate value of resistor R12 is calculated with the formula:

$$R_{12} = 4R\,(10)^A / S\,(NL)^B$$

Where: A = 1.9074

B = 0.97242

R = value of resistor R10 or R11, whichever is connected to resistor R12 for given feedback configuration.

S = output signal span (V2 - V0) driving resistor R12:

4V for 1 to 5V output

5V for 1 to 6V and 0 to 5V outputs

10V for 0 to 10V output.

Determining the final corrected non linearity as expressed in % of span (Figure 2) using the following equation

$$NL = 100\ [V_1-(V_2-V_O)(P_1-P_O)/(P_2-P_O)-V_O]\ /(V_2-V_O)$$

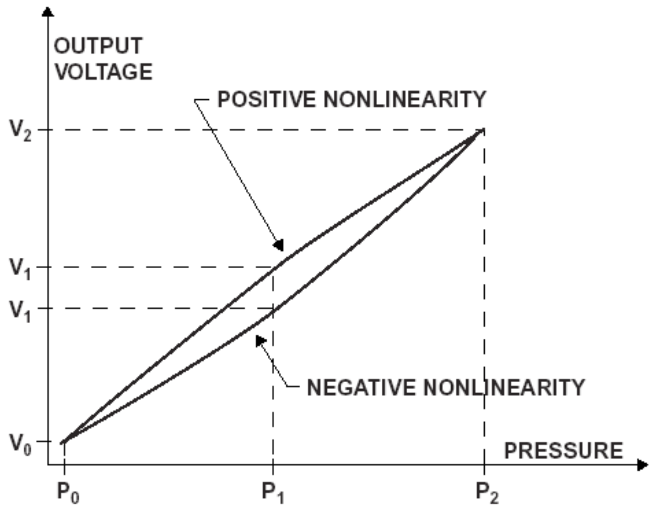


Figure 2 – Corrected Sensor Non Linearity Calculation

FREQUENCY RESPONSE

The sensor's frequency response can be tailored using capacitors C2 and C3. These components form low-pass filters with the amplifier's gain-setting resistors. Assuming C2 = C3 and R21 = R20, the −3 dB cutoff frequency is given by:

$$f = ½\ p\ C_2\ R_{21}$$

with the assumption that C2 = C3 and R21 = R20. Shaping the frequency response is commonly used to filter out unwanted high frequency noise.

VOLTAGE REGULATOR

An optional LT1121 voltage regulator is included to enhance robustness and electrical performance. It offers protection against reverse polarity, includes current and thermal limiting, and supports remote shutdown functionality. The regulator improves system resilience and ensures consistent performance regardless of variations in the supply voltage.

The output voltage of the LT1121 is defined by the resistor divider R22 and R23:

$$V_{out}=3.75V(1+R_{22}/R_{23})$$

This allows precise voltage tuning to match sensor and signal conditioning circuit requirements, further isolating performance from power supply variations and enhancing overall system stability

RATIOMETRIC APPLICATIONS

For ratiometric applications, the optional voltage regulator should not be used, and reference diode VR1 should be replaced by a resistor. The value of this resistor should not deliver a higher voltage than 1.26V across it at maximum operating power supply voltage in order to avoid saturation of the amplifiers.

Table 1. Typical Performance

Output Signal Option	Without Voltage Regulator		With Voltage Regulator		Units
	Voltage Output	4-20mA	Voltage Output	4 to 20mA	
Supply Voltage	9 to 30	10 to 30	11 to 30	12 to 30	V
Supply Current	2.4 at 15V	2.4 at 15V	2.7	2.7	mA
Output Voltage or Current Change Due to Supply Change	0.05 [1]	0.05 [1]	0.001	0.001	% of Span 10Vdc
Zero Range	±20	±20	±20	±20	% of Span
Zero Resolution	0.01	0.01	0.01	0.01	% of Span
Sensor Span Range (1mA)	33 to 115	33 to 115	33 to 115	33 to 115	% of Span
Span Calibration Resolution	0.05	0.05	0.05	0.05	% of Span
Output Noise	<0.01	<0.01	<0.01	<0.01	% of Span
Pressure Nonlinearity Corrected	0.02	0.02	0.02	0.02	% of Span
Sensor Excitation	1	1	1	1	mA

Note:

1. Function of Power Supply Rejection rate for the amplifier