MAX1478 REFERENCE MANUAL

(INCLUDES THE MAX1478EVKIT MANUAL)

Revision A, 01/00

EV KIT Quick Start
located in Chapter 12

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Revision A, January 2000
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How To Contact Maxim

This document contains all available information on the MAX1478 as of the date of printing. From time to time, additional information, or corrections may be added. The best source for up to date information will be the Maxim web site. Customers may also contact us at our technical support hotline.

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GENERAL DESCRIPTION

The MAX1478 is an Analog Sensor Signal Processor (ASSP) ASIC implemented in fine geometry mixed signal CMOS technology. It is optimized for piezoresistive pressure sensor calibration and temperature compensation. It can also be used with other resistive sensor types, such as accelerometers, strain gauges (with the addition of external components), etc. Calibration and compensation coefficients are stored in an internal 128-bit EEPROM. User-programmable digital EEPROM calibration coefficients correct the following:

- FSO (Full-Span Output)
- FSO TC
- Coarse Offset
- Fine Offset
- Offset TC

All corrections are performed in the analog signal path domain, allowing a typical settling time of better than 1ms. The output of the MAX1478 is ratiometric to the supply voltage. The built-in functionality enables the MAX1478 to support industrial, process, and aerospace applications, yielding a total accuracy which is typically within ±1.0% of the sensor's inherent repeatability error band over temperature.

Figure 1-1 shows the block diagram of the MAX1478. An internal 128-bit EEPROM holds the calibration coefficients determined during test (initial calibration and temperature compensation). These digital coefficients are retained by the EEPROM in the absence of VDD. Upon power-up, the digital coefficients are copied from the EEPROM into the five 12-bit internal static registers for the Offset DAC, FSO DAC, OFFTC DAC, FSOTC DAC, and the Configuration Register. This programs the unique analog characteristics of the MAX1478, required to calibrate and temperature-compensate the unique sensor element attached to it during test.

The sensor excitation is generated by an on-board Current Source, whose nominal value is programmed by the 12-bit FSO DAC. A second DAC, the FSOTC DAC, is used to modulate the sensor excitation current as a function of temperature to correct for sensor FSO TC errors. The differential output of the sensor is first fed into a summing junction, where a coarse offset correction can be performed using the Input Referred Offset (IRO) DAC. This correction is performed prior to signal amplification to extend the dynamic range of the system. The coarse offset-corrected sensor signal is then amplified by a 3-bit Programmable Gain Amplifier (PGA). After amplification, the signal can be corrected for fine offset errors using the Offset DAC. Offset Tempco errors are corrected using the OFFTC DAC. Finally, the calibrated and temperature-compensated signal is fed to an output buffer with tri-state capabilities to facilitate batch testing of sensor modules.

A four-wire digital interface is provided so the test system can communicate with the MAX1478 internal registers and EEPROM. These digital lines allow the devices to be bussed in the test system, minimizing the number of wires required for test. As few as two digital lines (SCLK and DI/O) may be used for communication during test.

The MAX1478 is optimized for calibrating and temperature compensating Silicon Piezoresistive Sensors (PRTs). In most cases, no additional external components are required. Depending on the power supply impedance, external bypass capacitor may be required. Additionally, external bypass capacitors may be added from pin OUT to VSS and from pin BDRIVE to VSS, to provide added ESD protection. The MAX1478 may also be used with other sensing elements, such as metal film strain gauges, accelerometers, etc.; however, some additional external components may be required.

The MAX1478 performs linear FSOTC compensation and linear Offset TC compensation. This will typically limit temperature compensation errors to about 1% over a wide range of temperature such as -40°C to +125°C. For applications requiring higher accuracy, an enhanced version of the MAX1478, the MAX1457, is available and can typically compensate sensor errors to within ±0.1% of the sensor repeatability errors. This is accomplished by using larger (16-bit) DACs and by adding vector table error correction of FSOTC and Offset TC to the basic analog functional block shown.

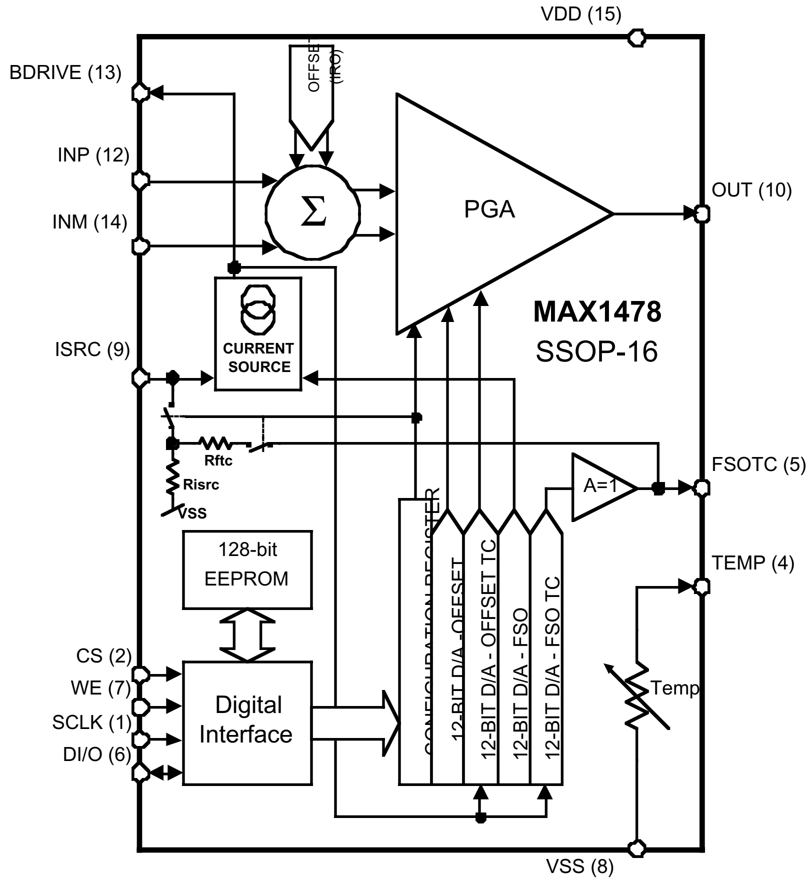


Figure 1-1

MAX1478 Block Diagram

Figure 1-2 shows the basic circuit configuration for the popular ratiometric voltage output configuration. Please note that these schematics show the minimum components needed and are intended for silicon PRTs. Other sensor types will require additional circuitry. In addition, an actual transducer module may need extra components for other features, such as overvoltage protection, reverse voltage protection, EMI/RFI noise suppression, etc. A second popular variant to the basic circuit is the regulated version shown in Figure 1-3. A low dropout regulator is used, which also exhibits low line and low load regulation errors, since the MAX1478 cannot compensate for these. Repeatable temperature related errors are unimportant, since they are compensated together with the sensor and MAX1478.

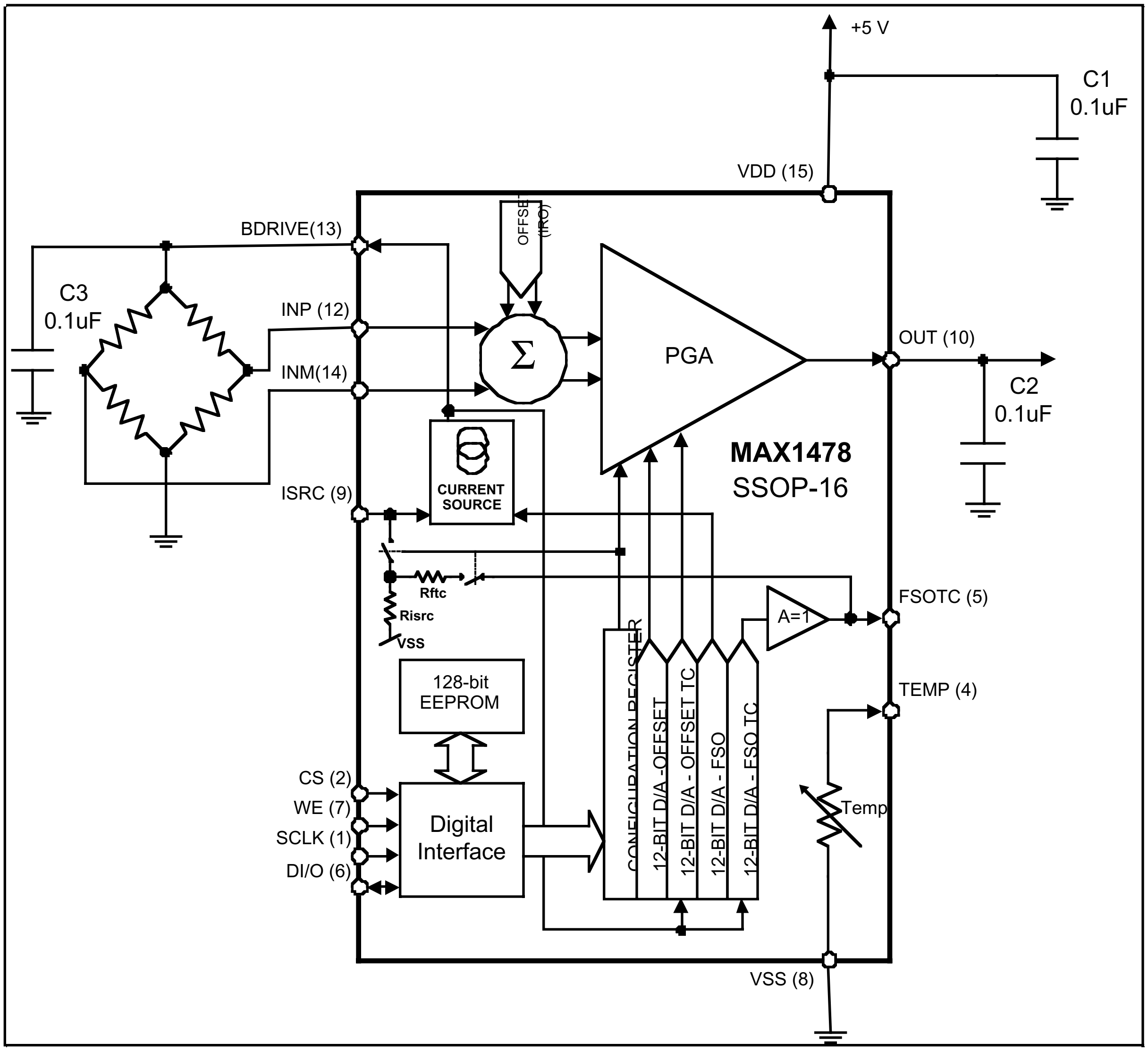


Figure 1-2

Circuit Schematic for Ratiometric Output Applications

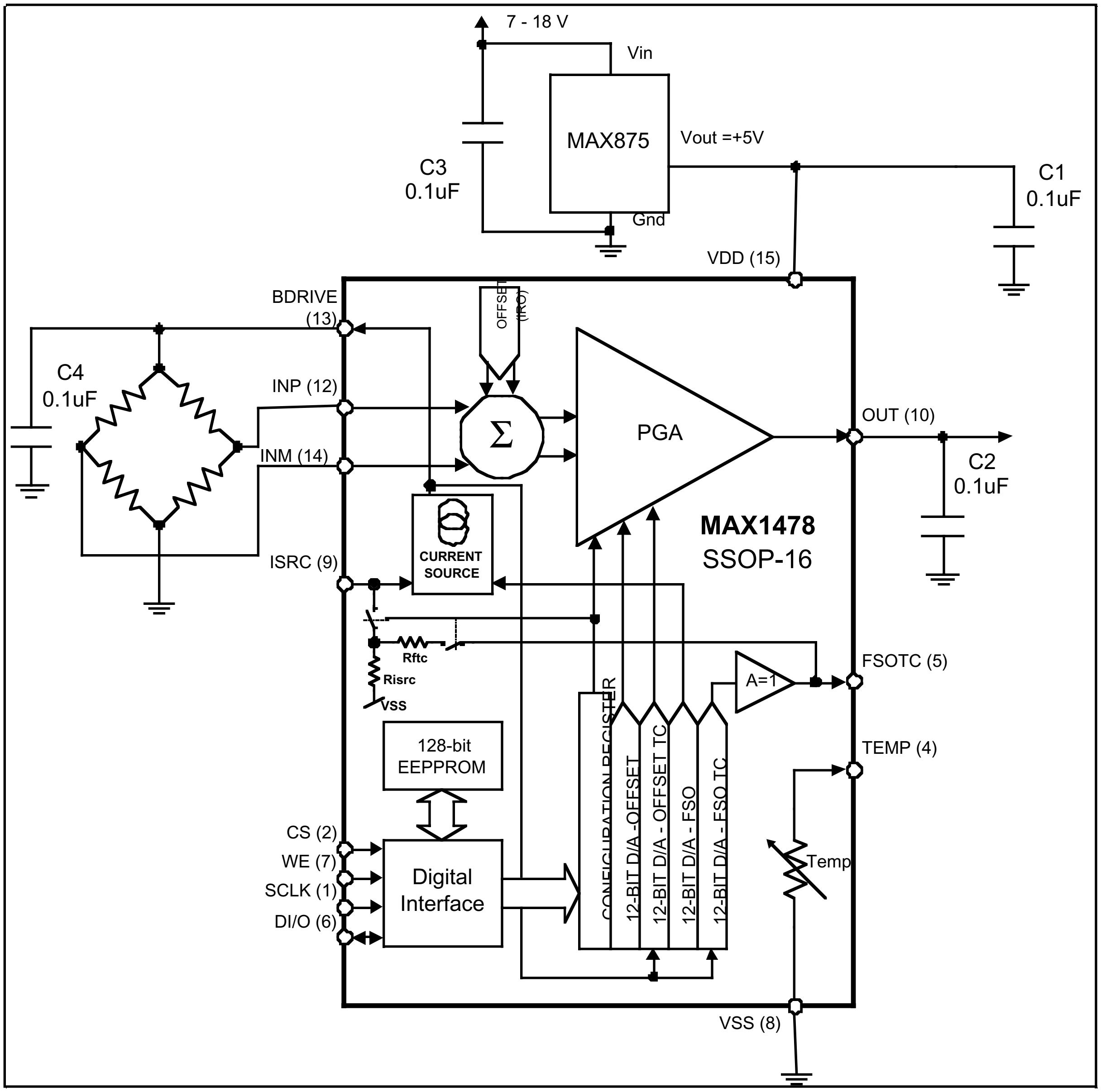


Figure 1-3

Circuit Schematic for Voltage Regulated Applications

XX-XXXX; Rev 0; 7/99

1% Accurate, Digitally Trimmed, Rail-to-Rail Sensor Signal Conditioner

General Description

The MAX1478 highly integrated, analog sensor signal processor is optimized for piezoresistive sensor calibration and compensation without any external components. It includes a programmable current source for sensor excitation, a 3-bit programmable-gain amplifier (PGA), a 128-bit internal EEPROM, and four 12-bit DACs. Achieving a total error factor within 1% of the sensor's repeatability errors, the MAX1478 compensates offset, offset temperature coefficient, full-span output (FSO), FSO temperature coefficient (FSO TC), and FSO nonlinearity of silicon piezoresistive sensors.

The MAX1478 calibrates and compensates first-order temperature errors by adjusting the offset and span of the input signal via digital-to-analog converters (DACs), thereby eliminating the quantization noise associated with digital signal path solutions. Built-in testability features on the MAX1478 result in the integration of three traditional sensor-manufacturing operations into one automated process:

- ***Pretest:*** Data acquisition of sensor performance under the control of a host test computer.
- ***Calibration and compensation:*** Computation and storage (in an internal EEPROM) of calibration and compensation coefficients computed by the test computer and downloaded to the MAX1478.
- ***Final test operation:*** Verification of transducer calibration and compensation without removal from the pretest socket.

Although optimized for use with piezoresistive sensors, the MAX1478 may also be used with other resistive sensors (i.e., accelerometers and strain gauges) with some additional external components.

Customization

For high-volume applications, Maxim can customize the MAX1478 for unique requirements. With a dedicated cell library consisting of more than 90 sensor-specific functional blocks, Maxim can quickly provide customized MAX1478 solutions.

Applications

Piezoresistive Pressure and Acceleration Transducers and Transmitters
Manifold Absolute Pressure (MAP) Sensors
Automotive Systems
Hydraulic Systems
Industrial Pressure Sensors
Strain-Gauge Sensors
Industrial Temperature Sensors

Features

- ♦ **Medium Accuracy (±1%), Single-Chip Sensor Signal Conditioning**
- ♦ **Rail-to-Rail® Output**
- ♦ **Sensor Errors Trimmed Using Correction Coefficients Stored in Internal EEPROM—Eliminates Laser Trimming and Potentiometers**
- ♦ **Compensates Offset, Offset TC, FSO, FSO TC, and FSO Linearity**
- ♦ **Programmable Current Source (0.1mA to 2.0mA) for Sensor Excitation**
- ♦ **Fast Signal-Path Settling Time (<1ms)**
- ♦ **Single +5V Supply**
- ♦ **Accepts Sensor Outputs from 10mV/V to 40mV/V**
- ♦ **Fully Analog Signal Path**

Pilot Production System

To simplify your pressure sensor design, Maxim has developed a fully automated pilot production system that will smooth the difficult transition from prototype to production. Details appear at the end of this data sheet.

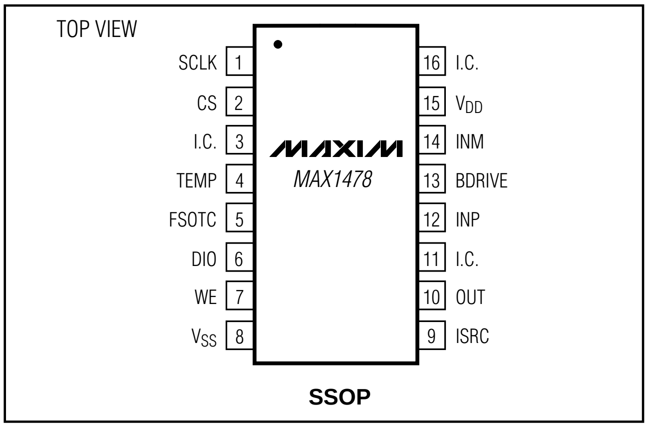
Ordering Information

PART	TEMP. RANGE	PIN-PACKAGE
MAX1478C/D	0°C to +70°C	Dice*
MAX1478AAE	-40°C to +125°C	16 SSOP

Dice are tested at T_A = +25°C, DC parameters only.

Functional Diagram appears at end of data sheet.

Pin Configuration



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ANALOG SECTION

The analog section of the MAX1478 consists of six functional blocks:

- Front-end summing junction and input referred offset (IRO) DAC
- Programmable instrumentation amplifier
- Output-summing junction and output buffer
- Programmable current source for sensor excitation
- Internal resistors and multiplexer
- Four 12-bit digital-to-analog converters

PROGRAMMABLE INSTRUMENTATION AMPLIFIER

Programmable instrumentation amplifier is fully differential and combines a 3-bit, plus sign, input referred coarse offset DAC (IRO DAC), a 3-bit programmable gain amplifier (PGA), an adder circuit for offset calibration and offset TC compensation, and a differential to single-ended output buffer with tri-state capabilities. Figure 3-1 shows the functional diagram of the instrumentation amplifier.

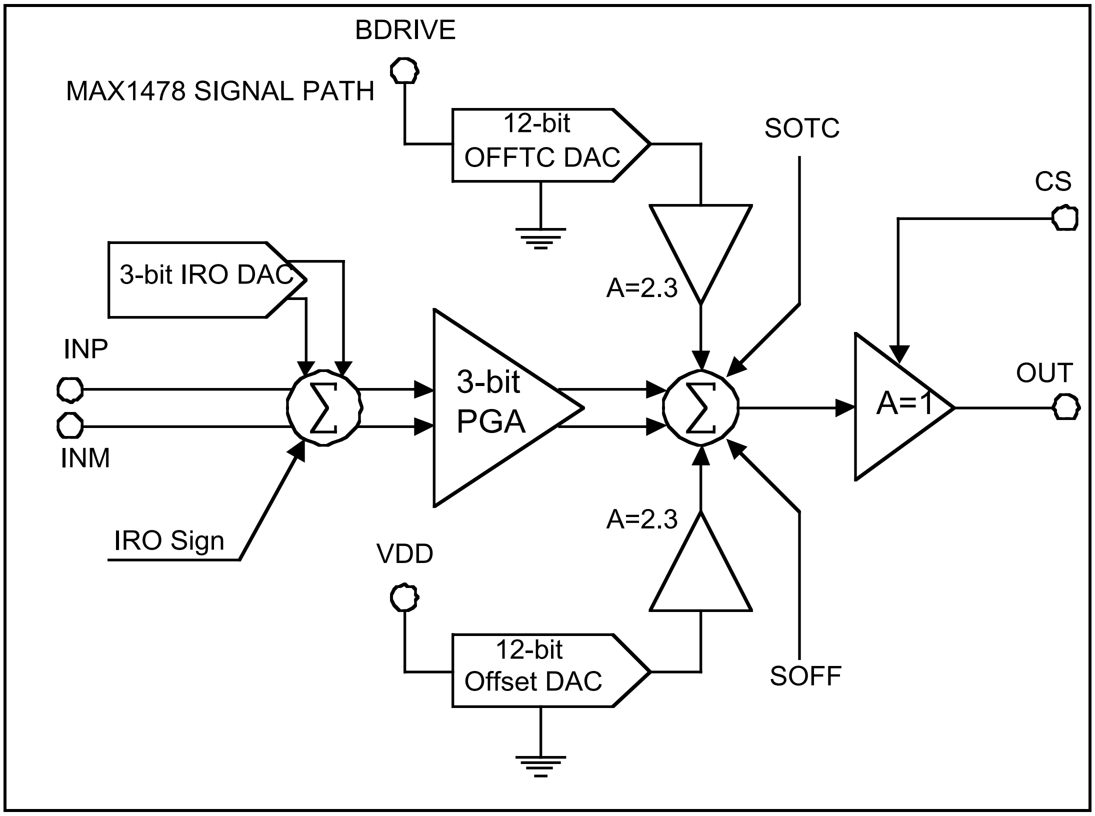


Figure 3-1

Signal Path Block Diagram

The Input-Summing Junction

The differential input voltage (INP-INM) is first fed into the input-summing junction implemented using a switched-capacitor architecture. The common mode input voltage can range from rail to rail, with a CMRR greater than 90dB. The typical input impedance is 1MΩ.

A 3-bit DAC (IRO DAC) is provided for front-end coarse offset corrections. This DAC takes its reference from VDD, which makes its output ratiometric to the supply. The DAC has a gain of 1/80, so that with a VDD of 5.0V, its full-scale output is 63mV. The 3 programming bits provide an input-referred resolution of 9mV per step (see Table 1 in the data sheet). The output of this DAC is summed with the differential input from the sensor according to the state of the IRO Sign Bit. If this bit is high, the output of the IRO DAC is added to the sensor signal, and if IRO Sign Bit is low, the output of the IRO DAC is subtracted from the sensor signal. The configuration register (see Digital Section) stores the IRO DAC value and the state of the IRO Sign Bit. The output of the input-summing junction is fed differentially to the PGA.

The Programmable Gain Amplifier

The PGA uses a differential chopper stabilized design implemented with CMOS switched-capacitor technology, and takes its input from the output of the input-summing junction. The gain is programmable using 3 bits described as PGA bits A2 - A0 inside the Configuration Register. These bits provide 8 gain levels in steps of 27 (Table 3-1). The amplifier exhibits very few offset TC errors (typically less than ± 0.5µV/°C) and very few gain TC errors (typically less than ± 50 ppm/°C). Signal linearity error is typically 0.01% VDD. The output of the PGA is fed to the output-summing junction.

PGA Bits			**PGA Gain (V/V)**	**Output-Referred IRO DAC Step Size (VDD = 5V)**
A2	**A1**	**A0**	**V/V**	**V**
0	0	0	41	0.369
0	0	1	68	0.612
0	1	0	95	0.855
0	1	1	122	1.098
1	0	0	149	1.341
1	0	1	176	1.584
1	1	0	203	1.827
1	1	1	230	2.070

Table 3-1

PGA Gain Table, Including the Effect of the IRO DAC

The Output-Summing Junction

The output of the PGA is fed differentially to the output-summing junction. The summing junction is implemented using a switched-capacitor architecture, and the output is fed to the output amplifier which has unity gain. The summing junction allows the summation of the PGA output, Offset, and OFFTC correction voltages. The Offset and OFFTC inputs are generated by their respective DACs. These two inputs are summed with respect to Vss. The state of their respective sign bits will determine if the voltage is summed into the inverting or non inverting side of the summing junction; thus, the magnitude of these two correction voltages can be added to (sign bit is high), or subtracted from (sign bit is low) the PGA output voltage.

A gain of approximately 2.3 is realized by the Offset and Offset TC summing nodes. Because the summing junction and signal path are implemented using switched-capacitor technology, their voltage equivalents can exceed the supply rails. The output of the output-summing junction is fed to the PGA Output Buffer.

PGA Output Buffer

The output stage takes its input from the summing junction and consists of a linear amplifier with an output swing capability to within 50mV of the either supply under no load conditions and the ability to sink or source 0.45mA while swinging to within 250mV of either supply. The output of this amplifier (OUT) becomes disabled if CS is brought low. See the digital section for details on the operation of this signal. When disabled, the typical output impedance is 1MΩ.

The output buffer will reach its normal output value within 100ms of VDD reaching the specified operating range. For additional ESD protection, an external 0.1 µF capacitor may be connected between OUT and VSS.

PGA Electrical Characteristics

(at VDD = 5 V, 25°C, unless otherwise noted)

PARAMETER	SYMBOL	CONDITION	MIN.	TYP.	MAX.	UNITS
General Characteristics						
Supply Voltage	VDD		4.5	5.0	5.5	V
Supply Current	IDD			3	6	mA
Analog Input						
Input Impedance	Rin			1.0		MΩ
Input Referred Offset TC				±0.5		µV/°C
Amplifier Gain Tempco		Any PGA gain		±50		ppm/°C
Amplifier Gain Non-Linearity				0.01		% VDD
Signal Response Time	tss			1.0		ms
Common Mode Rejection Ratio	CMRR	Common Mode voltage between V_{SS} and V_{DD}		90		dB
Input Referred Adjustable Offset Range		At minimum gain		±150		mV
Input Referred Adjustable FSO Range				10-40		mV/V
Summing Junction Gain		Offset or OFFTC		2.3		V/V
Summing Junction Gain Tempco		Offset or OFFTC		±50		ppm/°C
Analog Output						
Differential Signal Path Gain			41		230	V/V
Differential Signal Path Gain TC		Any PGA gain		±50		ppm/°C
Output Voltage Swing		No Load	VSS+0.05		VDD-0.05	V
Output Current Range		Vout =V_{SS}+0.25V to V_{DD}-.25V	-0.45 (sink)		0.45 (source)	mA

Table 3-2

Electrical Characteristics of Programmable Instrumentation Amplifier

Sensor Drive Description

The on-chip current source is implemented as a current mirror (Figure 3-2). The voltage at the output of the FSO DAC, together with resistor Risrc, sets the reference current “i” at pin ISRC (Current Source Reference Current) flowing through Risrc. This current is additionally modulated by a feedback resistor Rftc (correction of FSO TC errors). The total current “i” is then used as the reference to the current mirror, setting a bridge current as its multiple Ib=AA•Isrc, where AA is the current mirror gain(~14).

Two internal resistors are provided (Risrc and Rftc; both are 75kΩ nominal) which can be selected by the Internal Resistor Selection bit (IRS bit). When the IRS bit is high, the internal resistors are enabled, and when the IRS bit is low, the internal resistors are disabled, and two external resistors must be used in their place for proper current source operation. Note that it is possible to use both internal and external resistors simultaneously. It is also possible to add an external temperature-dependent device such as a transistor or high Tempco resistor to ISRC. This may be useful for applications involving strain gauge sensors. The IRS bit is located in the configuration register.

A third internal resistor, Rtemp (available at pin TEMP), is provided with a typical resistance of 100kΩ at 25°C. Unlike the other two internal resistors (Risrc and Rftc), Rtemp exhibits a very large Tempco of approximately +4600 ppm/°C. This resistor may prove useful for measuring temperature.

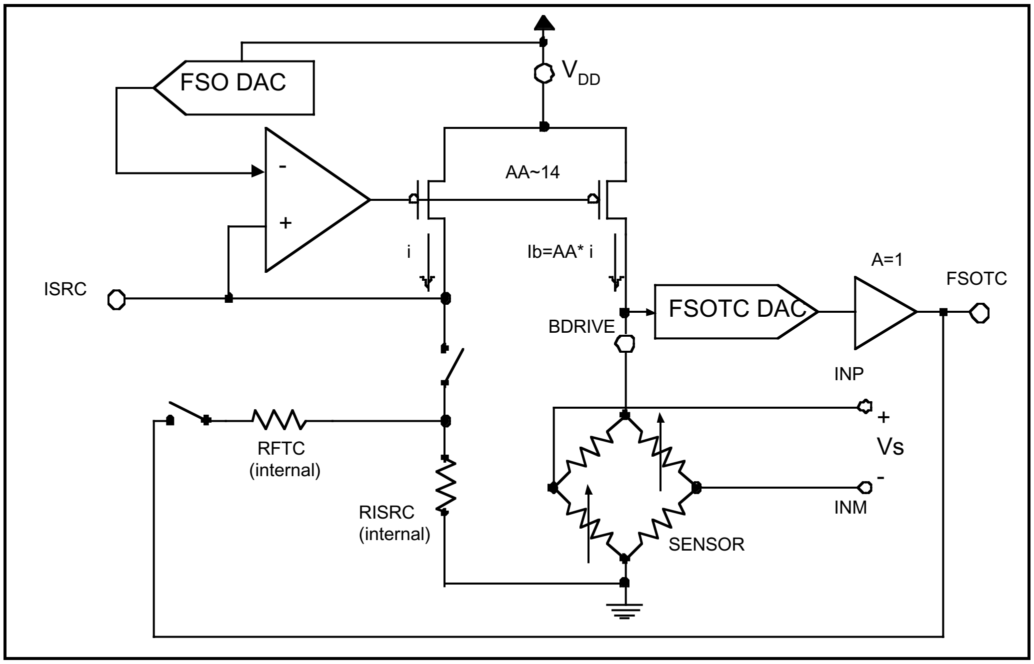


Figure 3-2

Bridge Drive Circuit

A constant current through the bridge results in any variation of bridge impedance (due to changing temperature) to be reflected as a change in bridge voltage. A piezoresistive sensor can exhibit typical temperature coefficient of bridge resistance up to 3000 ppm/°C. Thus, by monitoring and processing the bridge voltage, an excellent temperature sensor is established where the temperature is actually measured at the sensor element itself, minimizing thermal gradient errors between the pressure sensor and the temperature sensor and improving the temperature transients errors.

The FSODAC amplifier shown has a common mode input range from Vss+1.3 volts to Vdd-1.3 volts. This, in turn will restrict the operating voltage range of pin ISRC from Vss+1.3 volts to Vdd-1.3 volts, which can always be guaranteed by proper selection of the value for Risrc. Similarly, values for Rftc are chosen to guarantee that FSOTC is also operated within its valid common-mode voltage range.

Current Source Electrical Characteristics

Table 3-3 summarizes the electrical characteristics of the programmable current source, assuming values of 75kΩ for both Risrc and Rftc (these values are sensor-dependent).

(at V_{DD} = 5V, 25°C, unless otherwise noted)

PARAMETER	SYMBOL	CONDITION	MIN.	TYP.	MAX.	UNITS
Current Source						
Bridge Current			0.1	0.5	2.0	mA
ISRC Voltage Range			V_{SS}+1.3		V_{DD}-1.3	V
Bridge Voltage Range	Vbdrive		V_{SS}		V_{DD}-1.3	V
Current Source Output Impedance				100		kΩ
Current Mirror Ratio	AA			14		I/I
FSOTC Voltage Swing		no load	V_{SS}+0.3		V_{DD}-1.3	V
FSOTC Current Drive		V_{FSOTC} =2.5V	-20		20	µA

Table 3-3

Electrical Characteristics of the Sensor Drive Circuit

The current source output, BDRIVE, has an output range of Vss to Vdd-1.3 volts. However, since VFSOTC has a more restricted common mode input range (Vss+0.3 volts to Vdd-1.3 volts), the sensor excitation voltage will normally be restricted to the range of Vss+0.3 volts to Vdd-1.3 volts.

DIGITAL-TO-ANALOG CONVERTERS

Digital-to-Analog Converter Description

The MAX1478 contains four 12-bit sigma-delta digital-to-analog converters (DACs):

- Offset DAC
- OFFTC DAC
- FSO DAC
- FSOTC DAC

Each DAC has its reference voltage supplied internally. FSO DAC and Offset DAC take their reference from VDD; FSOTC DAC and OFFTC DAC take their reference from BDRIVE. All DAC converters, as well as the control registers, are updated according to the state of the WE pin (described in detail in the Digital Section). With VDD = 5V, the typical DAC resolution is 1.22mV per bit. However, FSOTC DAC and OFFTC DAC take their reference from BDRIVE which is normally operated near VDD/2, hence the output step size of these two DACs will normally be less than 1.22mV. The outputs of Offset DAC and OFFTC DAC are gained up by a factor of 2.3 in the signal path output-summing junction. This gain is established to increase the offset and offset TC trimming range, respectively. As a result of this gain, the step size as seen at OUT is increased.

All DACs retain their values while CS is low (but will be reloaded on the next CS low-to-high transition), and have a settling time which is typically less than 50mS. This value is proportional to the change in code.

DIGITAL SECTION

The digital section of the MAX1478 contains interfaces to the internal EEPROM, DACs, Configuration Register, signal path, PGA, and the test system. The digital section performs the following operations:

- Provide a user test-system interface using pins CS, SCLK, DI/O, and WE
- Decode and execute commands issued on DI/O
- Perform EEPROM erase/write cycles
- Read EEPROM contents into the DACs and configuration register
- Provide direct test system access to the DACs and configuration registers
- Interface with the PGA, Sign bits, IRS, and enable/disable the output stage

POWER-UP INITIALIZATION

Upon power-up, once VDD reaches approximately 3 volts, the power-on reset circuit initiates its sequence. The sequence begins with a delay of 10 microseconds to allow the power to become stable, during which the four digital programming lines are pulled to their default states (if left unconnected) as shown in Table 4-1. After this wait period, the DACs and configuration register are initialized from EEPROM. Five static registers are provided to store the contents of the four DACs and the configuration word. The configuration word is used to program the signal path and PGA characteristics. The 5 registers can be loaded from EEPROM or directly from an external test system, depending on the state of the Update Mode (“U”) bit. The Update Mode bit is programmed by the test system, and it is bit 5 of the 6-bit Initialization sequence which will be described later. Upon power-up, the “U” bit is set to “0” directing the contents of the EEPROM to be loaded into the five static registers. The Update Mode Bit is not accessible to the test system and its state cannot be read by the user. Upon power-up, the digital section begins monitoring its input pins for commands from the test system. If the WE pin is high (default state), the EEPROM contents will be reloaded periodically into the five registers at approximately 400 times per second.

PIN NAME	STATE	ACTION
CS	Pulled High	Enables communication and analog output.
SCLK	Pulled Low	If a false clock edge appears, enter Lockout Mode.
DI/O	Pulled Low	Assures that data is not accidentally clocked in.
WE	Pulled High	EEPROM data is refreshed 400 times per second.
OUT	Active	Output amplifier becomes active.
LIMIT	Set to Default Value	Output voltage is limited to about 92% of VDD.

Table 4-1

Default State Of Key I/O Pins

After power-up, or after a low-to-high transition of the CS (Chip Select) line, the Lockout Bit is reset to “0”. The Lockout Bit is used to allow/disallow the test system from communicating with the MAX1478. If the Lockout Bit is “0”, communication is allowed; if the Lockout Bit is “1” communication is not allowed. The Lockout Bit will be set to “1” if the Initialization Sequence fails, i.e., the unique 6-bit Init pattern is not detected. The Lockout Bit is not accessible by the test system and its state cannot be read by the user. After power-up, the first command, if any, issued by the test system must be the 6-bit Initialization Sequence. Thereafter, any number of command words may be issued so long as both VDD and CS are kept high.

After the DACs are initially loaded, approximately 50mS are required for their analog outputs, as well as the signal path, PGA, and Current Source to reach steady state values. The power-on reset sequence is summarized in Table 4-2.

STEP	ACTION
1	Wait for the power-up voltage threshold to be reached.
2	Initiate delay of 10 microseconds.
3	Set the state of the digital I/O pins to default mode.
4	Set Update Mode Bit and Lockout Mode Bit to “0”.
5	Load the 5 static registers from the EEPROM, and Begin monitoring the digital lines for the Init Sequence.
6	If WE pin is high, update from EEPROM 400 times per second.

Table 4-2

Power-Up Reset Procedure

DESCRIPTION OF THE DIGITAL I/O PINS

CS, Chip Select

This input pin is always internally pulled to VDD via a 1MΩ resistor, assuring that if the pin is left unconnected, the MAX1478 will be enabled and operate normally. Assuming that VDD is held high, the following steps take place on any rising edge of CS:

- The five internal registers are updated according to the state of the “U” bit
- The amplifier output stage is enabled
- The Lockout bit is reset to “0”
- The MAX1478 begins to monitor the digital input lines for the Init Sequence
- The five internal registers are updated at a rate determined by the state of the WE pin

In normal device operation, after calibration and compensation, the CS line will be left unconnected. The CS line is primarily for test and calibration purposes. If the CS line is brought low, the following actions take place:

- The amplifier output stage will be placed in a high impedance state (Zout ~ 1MΩ)
- The DACs will retain their values
- The Current Source will remain active
- The states of SCLK, DI/O, and WE are ignored
- SCLK and DI/O will be pulled low via a 1MΩ resistor
- WE will be pulled to VDD via a 1MΩ resistor

In a multiple device test system where SCLK and DI/O are bussed, CS is used to address individual devices. In noisy environments, a small value capacitor, not larger than 0.01µF, may be placed between CS and VSS, close to the chip to prevent false transitions from possibly corrupting the

MAX1478 registers. **Important note: after the MAX1478 is programmed, the CS line must be left unconnected; do not tie CS to VDD or add external pull-up/pull-down resistors.**

SCLK, Serial Clock

The serial input clock pin is used by the test system to load commands and data into the MAX1478. This signal will always be generated by the test system. Data on DI/O is sampled on the rising edge and must therefore always transition on the falling edge of SCLK. A minimum of 200µS is required after the rising edge of CS, before the first SCLK rising edge can occur. The MAX1478 is fully static and the period of SCLK can be any value greater than 100µS, as long as VDD and CS are both held high.

If this pin is left unconnected, it will be pulled to VSS via an internal 1MΩ resistor. This will insure that data is not inadvertently written to the MAX1478. In noisy environments, a small value capacitor, not larger than 0.01µF, may be placed between SCLK and VSS, close to the chip to prevent false transitions from possibly corrupting the MAX1478 registers. Optionally, after the MAX1478 is programmed, the SCLK line can be permanently tied to VSS.

DI/O, Data Input/Output

This is a bi-directional pin used to input commands and data into the MAX1478, and also to read data from the internal EEPROM. This pin has an internal 1MΩ resistor to VSS. This pull-down resistor is always present regardless of the state of CS, regardless of whether DI/O is acting as an input or output pin. If this pin is left unconnected, this pull-down insures that if a parasitic SCLK occurs, a low will be loaded into the MAX1478. This would place the MAX1478 into Lockout Mode (since the first bit of the Init Sequence must be a “1”), and prevent any accidental alteration of the register contents. In noisy environments, a small value capacitor, not larger than 0.01µF, may be placed between DI/O and VSS, close to the chip to prevent noise on SCLK from possibly corrupting the MAX1478 registers. Optionally, after the MAX1478 is programmed, the DI/O line can be permanently tied to VSS.

DI/O will always serve as an input pin, except after the 16th rising edge of SCLK of the READ EEPROM command after which DI/O becomes an output pin with an undetermined state. Then, 200µS after the next falling edge of SCLK, DI/O will contain the logical state of the bit in EEPROM which was addressed by the READ EEPROM command. SCLK must then be held low while the test system reads the state of the DI/O pin. After reading the data, the test system must issue a low-to-high transition on CS.

WE, Write Enable

This is a dual function input pin. It is sampled by the MAX1478 during EEPROM Erase/Write commands to determine if the operation can be performed. Additionally, the state of this pin is sampled by the MAX1478 to determine how to update EEPROM data into its five internal registers. This pin has an internal 1MΩ resistor to VDD. This pull-up resistor is always present, regardless of the state of CS. If this pin is left unconnected, this pull-up will insure that the test-system interface can be implemented using only two (SCLK and DI/O) or three (SCLK, DI/O, and CS) digital lines. In noisy environments, a four-wire system could be implemented which would also include WE to minimize the chances of accidental alteration of EEPROM data. Additionally, a small value capacitor, not larger than 0.01µF, may be placed between WE and VSS, close to the chip to prevent noise on WE. Optionally, after the MAX1478 is programmed, the DI/O line can be permanently tied to VSS or VDD, depending on the desired operating mode.

During an EEPROM alteration operation (Write or Erase), the WE pin must be held high prior to the first rising edge of the 16-bit command and then must not be lowered until the subsequent delay period Twrite = 50mS has expired. If WE is held low during this entire period, no EEPROM alteration will be performed. If WE transitions during this period, unpredictable results may include failure to Write the selected bit, failure to Erase all 128 EEPROM bits, or the alteration of unwanted bits.

During normal operation, other than an EEPROM Write or Erase cycle, the MAX1478 will monitor the state of the WE pin to determine how EEPROM data will be loaded into its five internal registers. If WE is low during the power-up reset cycle, the contents of the EEPROM will be loaded once into the five internal registers. Subsequently, the internal registers will not be reloaded from EEPROM unless VDD transitions, causing another power-up reset cycle to take place, or unless CS transitions from low to high, or unless WE is taken high. After power-up or after a low-to-high transition on CS, the WE pin may be toggled at will to control the register update rate. Any time that WE is held high, the registers will be reloaded 400 times per second. Note that it is only necessary to load the EEPROM contents into the five MAX1478 registers once after power-up; however, in high EMI emission environments or applications where the supply voltage may not be clean, the continuous update mode (WE = VDD) provides a very fast error recovery should the internal registers become corrupted.

THE COMMUNICATION INITIALIZATION SEQUENCE

Communication with the MAX1478 is accomplished serially. A minimum of two lines is required for communication (SCLK and DI/O) and two additional lines may be used to provide enhanced communication functionality (CS and WE). After power-up or after a low-to-high transition of CS, the first command, if any, issued by the test system must be the 6-bit Initialization Sequence. Thereafter, any number of 16-bit command words may be issued so long as both VDD and CS are kept high. The Initialization sequence (Figure 4-1) increases the robustness of the communication protocol, particularly in noisy test-system environments. To prevent erroneous commands from being accepted by the MAX1478, a unique 6-bit keyword initialization sequence has been defined (Init Sequence). This Init Sequence must be the first command issued after power-up or after any low-to-high CS transition so the MAX1478 can accept test-system commands. Note that the absence of an Init Sequence does not prevent the MAX1478 from its normal power-up initialization, including operation of the analog signal path, PGA, and Current Source. The Init Sequence can be issued at any time (but not less than 0.2mS) after VDD and/or CS rising.

The Init Sequence performs two functions. First, the state of bit 5 of the 6-bit sequence is used to set the “U” bit. Second, if the unique 6-bit pattern is not detected, the Lockout Bit is set to “1” preventing any subsequent communication from taking place until the VDD and/or CS lines are toggled from high to low and back to high again. If the Init Sequence fails, SCLK and DI/O are ignored until the next transition of VDD or CS. CS will continue to function and WE will only be used to determine the EEPROM to register update mode. The MAX1478 analog section (Signal Path, PGA, and Current Source) will continue to function. For most applications, it is recommended that WE be tied low.

Upon power up, the “U” bit is set low, forcing an update of the five internal registers from EEPROM. If, after power-up, the state of the “U” bit is left low, subsequent low-to-high transitions of CS will cause the five internal registers to be updated from EEPROM. If the “U” bit is set high, subsequent low-to-high transitions of CS will not cause an update of the internal registers from EEPROM, so long as VDD is kept high. Thus, with the “U” bit set high, the internal registers will retain the last value written into them by the test system until VDD is lowered. This feature enhances test and calibration. Note that the Init Sequence cannot be issued more than once after power-up or after a low-to-high transition of CS.

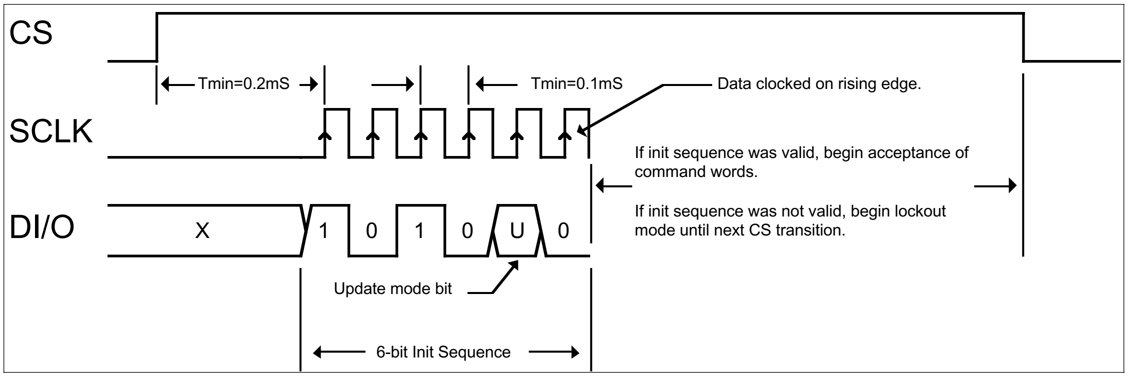


Figure 4-1

Initialization Sequence Timing Diagram

THE CONTROL WORD

The MAX1478 recognizes a total of 16 control words (Table 4-3). Control words are 16-bits wide and are issued by the test-system to perform functions such as erasing the EEPROM, writing to DACs, etc. Every control word (Figure 4-2) consists of 16 bits divided into two fields: the data field and the command field. The data field consists of the first 12 bits, with the LSB being clocked in first. The command field follows the MSB of the data field and is also clocked in LSB first. The last bit of the control word is the MSB of the command field. A subsequent rising edge of SCLK (i.e., a 17th bit) will be treated as the first bit of the next control word. All data is loaded on the rising edge of SCLK and must therefore transition from the falling edge of SCLK.

Control words will not be accepted by the MAX1478 unless one Init Sequence has been previously issued. Do not precede every Control word with an Init Sequence. After the first Init Sequence is detected, every subsequent set of 16 SCLK low-to-high transitions will be interpreted as a control word (Figure 4-3). Once the MAX1478 has detected the Init Sequence, any number of control words may be issued and will be accepted so long as CS is held high. The exception is the READ EEPROM command, which necessitates a low-to-high CS transition after the data bit has been read.

CONTROL WORD	HEX CODE	CM3	CM2	CM1	CM0	DESCRIPTION
NO OPERATION	00h	0	0	0	0	The control word is ignored.
ERASE EEPROM	01h	0	0	0	1	Forces all 128 bits to “0”. The data field contents are ignored. Command must be followed by a 50mS delay, and then an END EEPROM WRITE Command at address 0.
BEGIN EEPROM WRITE	02h	0	0	1	0	Initiates the internal write sequence which will set the bit indicated to “1”. Must be followed by a 50mS delay, and then an END EEPROM WRITE (at the same address) command.
READ EEPROM	03h	0	0	1	1	Returns the state of one of the 128 bits in memory on DI/O.
RESERVED	04h	0	1	0	0	Reserved by MAXIM, do not use.
END EEPROM WRITE	05h	0	1	0	1	Completes the internal write, erase sequence. This command must follow any ERASE EEPROM or BEGIN EEPROM WRITE command. Wait 1mS after issuing command.
WRITE TO CONFIGURATION REGISTER	08h	1	0	0	0	Writes the 12-bit value contained in the data field of the command directly to the Configuration register. Does not affect the EEPROM contents. Must be followed by a LOAD REGISTER command.
WRITE TO OFFSET DAC REGISTER	09h	1	0	0	1	Writes the 12-bit value contained in the data field of the command directly to the OFFSET TC DAC register. Does not affect the EEPROM contents. Must be followed by a LOAD REGISTER command.
WRITE TO OFFSET TC DAC REGISTER	0Ah	1	0	1	0	Writes the 12-bit value contained in the data field of the command directly to the OFFSET DAC register. Does not affect the EEPROM contents. Must be followed by a LOAD REGISTER command.
WRITE TO FSO DAC REGISTER	0Bh	1	0	1	1	Writes the 12-bit value contained in the data field of the command directly to the FSO DAC register. Does not affect the EEPROM contents. Must be followed by a LOAD REGISTER command.
WRITE TO FSOTC DAC REGISTER	0Ch	1	1	0	0	Writes the 12-bit value contained in the data field of the command directly to the FSOTC DAC register. Does not affect the EEPROM contents. Must be followed by a LOAD REGISTER command.
LOAD REGISTER	06h 07h 0Dh 0Eh 0Fh	0 0 1 1 1	1 1 1 1 1	1 1 0 1 1	0 1 1 0 1	This command is issued after any WRITE TO REGISTER command to load in the data. Use only one command. Any of the 5 commands may be used.

Table 4-3

Summary Of The Command Words

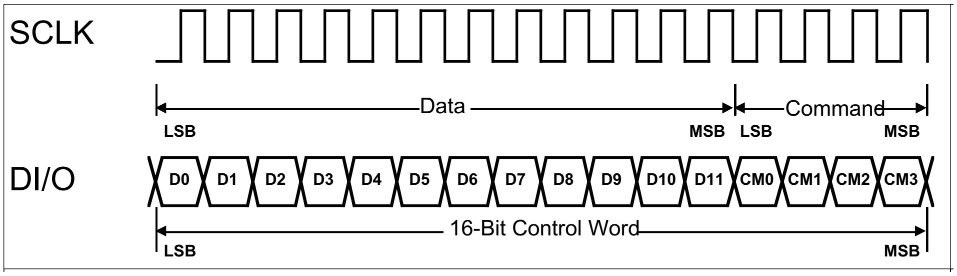


Figure 4-2

Control Word Timing Diagram

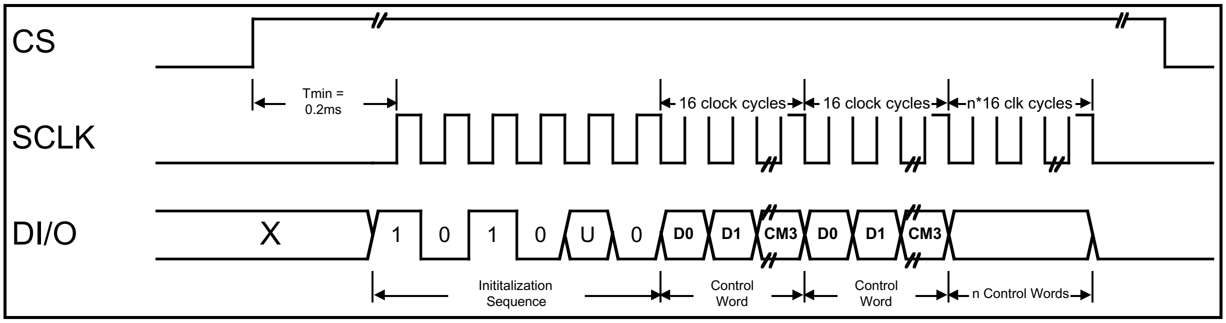


Figure 4-3

Communication Sequence Timing Diagram

THE INTERNAL EEPROM

The MAX1478 contains an integrated 128-bit EEPROM. This memory is used to store the calibration and compensation coefficients when power is shut off. Upon power-up or when instructed by the test system, the EEPROM memory contents are copied into the five internal registers. The EEPROM is organized as eight 16-bit words, each comprised of two fields: the register ID field and the data field (Figure 4-4). The EEPROM memory organization is shown in Figure 4-5.

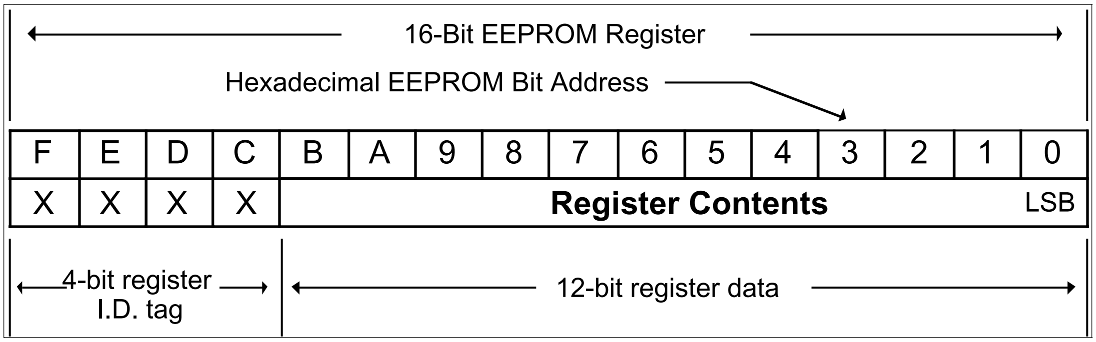


Figure 4-4

EEPROM Register Organization

The most significant 4 bits of each 16-bit EEPROM register contain a unique ID Tag. These ID Tags must be programmed by the test system as indicated in the shaded areas of Figure 4-5. Failure to do this will result in unpredictable behavior from the MAX1478. The MAX1478 will ignore (not process) any EEPROM registers which contain an ID Tag of “0000”; this includes registers 5 through 7.

The EEPROM is shipped from the factory in an unknown state and must be erased before it can be programmed. Erasing the memory consists of setting all 128 bits to “0”. It is not possible to selectively set individual bits to “0”. Writing to the EEPROM consists of setting selected bits to “1”, and this must be performed one bit at a time. The EEPROM can be read by the test system one bit at a time and after each bit is read, the test system must issue a low-to-high transition of the CS line.

The EEPROM requires a high-voltage charge pump generator, which has been integrated into the MAX1478. This charge pump generates voltages of up to 20 volts. The ERASE EEPROM, BEGIN EEPROM WRITE, and END EEPROM WRITE commands control the charge pump. The charge pump is turned off when the EEPROM is not being programmed. Normally, the EEPROM will be programmed only once after the calibration and compensation coefficients have been determined by the test system, since the test cycle can be more efficiently performed by writing directly to the five internal registers. To insure the highest reliability and the longest data retention, the EEPROM should not be erased more than 100 times and should only be erased or written to at room temperature.

Register 0	**EE Address**	0F	0E	0D	0C	0B	0A	09	08	07	06	05	04	03	02	01	00
	Contents	1	0	0	0						**Configuration**						**LSB**
Register 1	**EE Address**	1F	1E	1D	1C	1B	1A	19	18	17	16	15	14	13	12	11	10
	Contents	1	0	0	1	**MSB**					**Offset**						**LSB**
Register 2	**EE Address**	2F	2E	2D	2C	2B	2A	29	28	27	26	25	24	23	22	21	20
	Contents	1	0	1	0	**MSB**					**Offset TC**						**LSB**
Register 3	**EE Address**	3F	3E	3D	3C	3B	3A	39	38	37	36	35	34	33	32	31	30
	Contents	1	0	1	1	**MSB**					**FSO**						**LSB**
Register 4	**EE Address**	4F	4E	4D	4C	4B	4A	49	48	47	46	45	44	43	42	41	40
	Contents	1	1	0	0	**MSB**					**FSO TC**						**LSB**
Register 5	**EE Address**	5F	5E	5D	5C	5B	5A	59	58	57	56	55	54	53	52	51	50
	Reserved	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Register 6	**EE Address**	6F	6E	6D	6C	6B	6A	69	68	67	66	65	64	63	62	61	60
	Contents	0	0	0	0						**User defined bits**						
Register 7	**EE Address**	7F	7E	7D	7C	7B	7A	79	78	77	76	75	74	73	72	71	70
	Contents	0	0	0	0						**User defined bits**						

▨ = Reserved Bits which must be programmed as indicated for proper device operation.

Figure 4-5

EEPROM Organization

Registers 5 through 7 are not used by the MAX1478 and are never read by the device. Register 5 is reserved for future functionality and all 16 bits must be programmed by the test system to “0” for proper operation of the chip. The lowest 12 bits of registers 6 and 7 are available to the user. They may be assigned for storing date code, serial number, checksums, or any other useful information. Whether they are used or not, it is essential that the 4 MSBs of these two registers be programmed as shown in Figure 4-5; failure to do this will result in unpredictable behavior of the MAX1478.

Erasing The EEPROM

When the MAX1478 is received from the factory, its memory contents are unknown and the EEPROM must be erased. Individual bits cannot be set to “0”; thus any requirement to set a bit to “0” will necessitate an EEPROM erase cycle. The erase process sets all 128 bits to “0” and takes approximately 50mS. It should only be performed with VDD set to 5V and at room temperature. The data field of the ERASE EEPROM command is ignored and can be any value. The procedure for erasing the EEPROM (Figure 4-6) is outlined below:

1. Issue a low-to-high transition on CS
2. Issue the Init Sequence
3. Raise WE
4. Issue an ERASE EEPROM command
5. Wait 50mS
6. Issue an END EEPROM WRITE command at address 0
7. Wait 1mS
8. Optionally Read back all bits and verify they are set to “0”

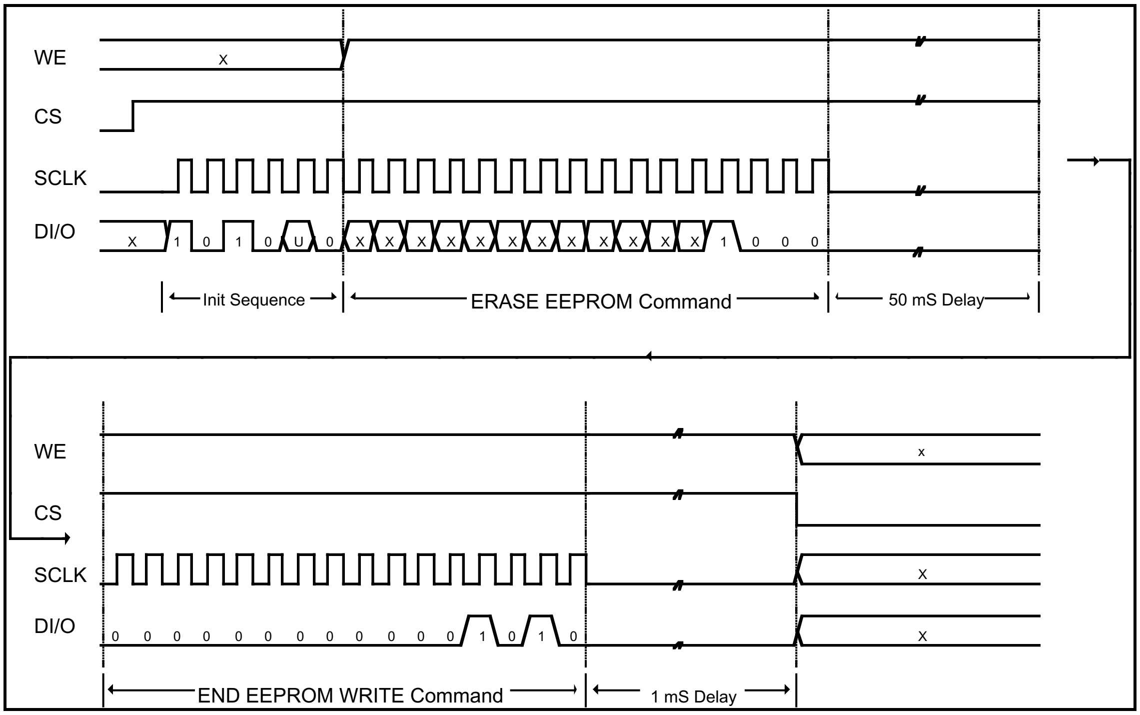


Figure 4-6

ERASE EEPROM Timing Diagram

Writing To The EEPROM

After calibration and compensation is completed, a list should be made containing all the address bits that must be set to “1”. An ERASE EEPROM command should be issued. Programming each bit will require approximately 50mS; thus, if it is necessary to program all 128 bits to a “1”, about 7 seconds will be required. In practice, only a small percentage of the 128 bits are typically set to “1” and programming time is usually less. Programming should only be performed with VDD set to 5V and at room temperature. The procedure is outlined below:

1. Erase the EEPROM
2. Issue a low-to-high transition on CS
3. Issue an Init Sequence
4. Raise WE
5. Issue a BEGIN EEPROM WRITE at the desired bit address
6. Wait 50mS
7. Issue an END EEPROM WRITE command at the desired bit address
8. Wait 1mS
9. Repeat steps 5-8 for all other bits which must be set to “1”
10. Optionally Read back all bits and verify they are set correctly

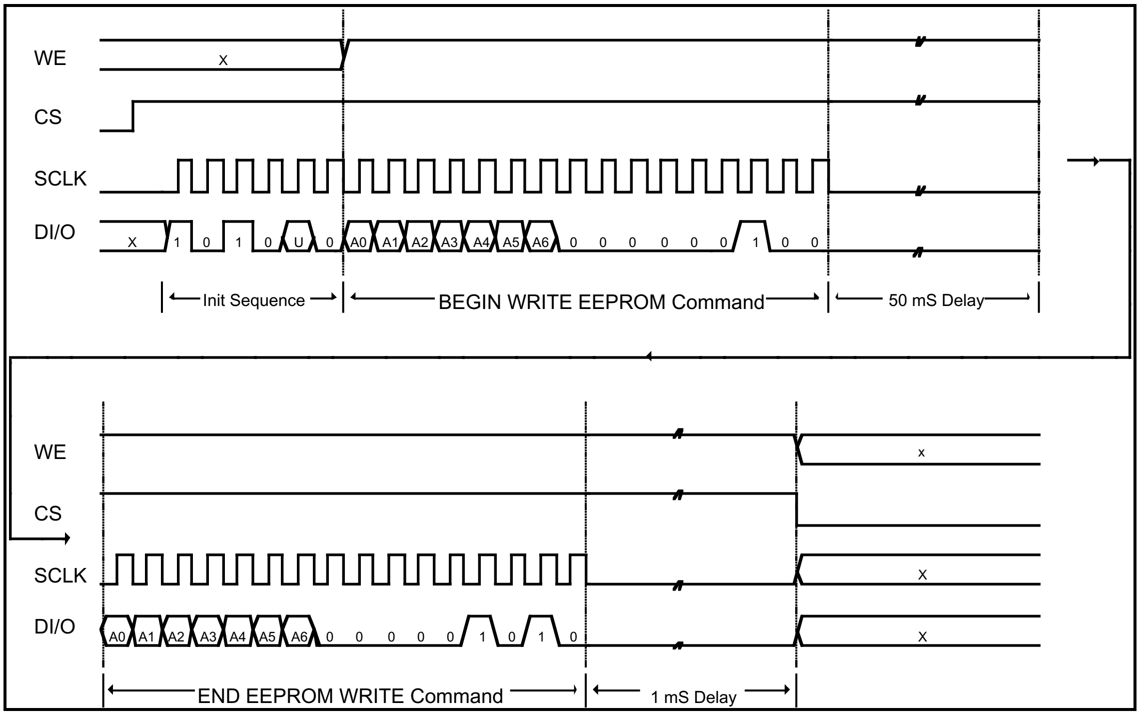


Figure 4-7

EEPROM WRITE Timing Diagram

Reading The EEPROM

This is the only operation that cannot be performed sequentially after a single Init Sequence, since it necessitates a high-to-low transition of CS after each EEPROM bit is read. This is also the only command that changes the state of DI/O to an output. After issuing the READ EEPROM command, the next clock transition will place the contents of the EEPROM bit addresses A6-A0 (the contents of A7-A11 are ignored) on the DI/O pin. This is a fully static operation and the data will remain valid so long as SCLK and CS do not change states. After reading the EEPROM bit, the test system must lower CS. This operation should only be done with VDD set to 5V and can be performed at any temperature.

1. Issue a low-to-high transition on CS
2. Issue an Init Sequence
3. Issue a READ EEPROM command at the desired bit address
4. Issue a single clock transition (DI/O is don’t care)
5. Wait a minimum of 200µS
6. Read the state of the DI/O bit
7. Lower CS

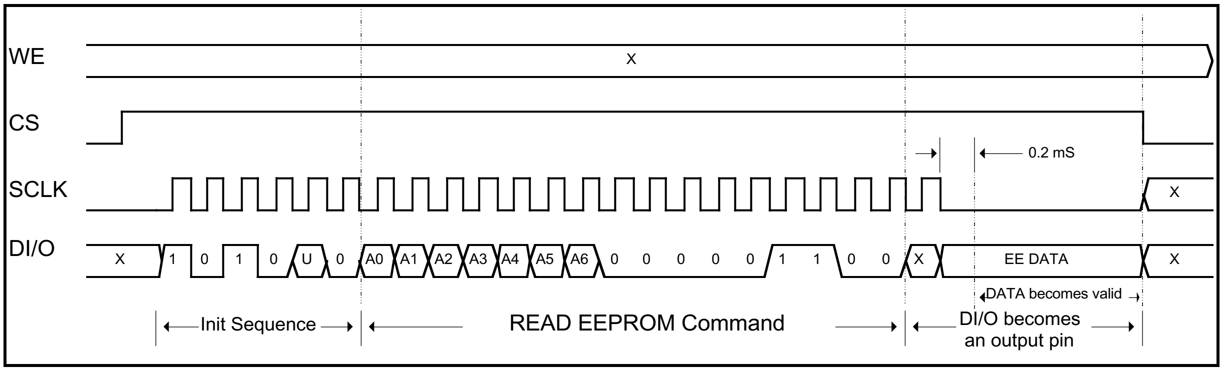


Figure 4-8

EEPROM READ Timing Diagram

THE CONFIGURATION REGISTER

This is the first register in EEPROM (bit addresses 0-0Fh). During test, it can also be written to directly, along with the 4 DAC registers. This provides much faster test communication than using the EEPROM for calibration and temperature compensation. Table 4-4 describes the internals of the Configuration Register.

Bit Number	Function
0	Offset TC Sign Bit, SOTC
1	Offset Sign Bit, SOFF
2	PGA Gain Bit (MSB), A2
3	PGA Gain Bit, A1
4	PGA Gain Bit (LSB), A0
5	RESERVED, must be “0”
6	RESERVED, must be “0”
7	Internal Resistor Selection (IRS) Bit
8	Input Referred Offset (IRO) Sign Bit
9	Input Referred Offset (MSB), IRO2
10	Input Referred Offset, IRO1
11	Input Referred Offset (LSB), IRO0

Table 4-4

Detail of Configuration Registers

REGISTER COMMUNICATION

Initial calibration and compensation will require loading and reloading many different coefficients into the MAX1478, as temperature and pressure are changed. This process should not be performed using the internal EEPROM for two reasons. First, it is not possible to write to the EEPROM at any temperature other than 25°C. Second, writing to the EEPROM is a very slow process that requires approximately 5 seconds. A method has been provided whereby the 4 DACs and the Configuration Register can be accessed directly without the need for the EEPROM. The test system can place values in any of these five registers, and the value will be retained until it is changed by the test system or until the supply (VDD) is removed. The five registers can be loaded sequentially after one Init sequence or they can be loaded individually, at will. The operation requires only a few milliseconds. Figure 4-9 contains the timing diagram for a single register write command. Note that although the example shows a write to the Configuration Register, it could also have been a write to any of the 4 DACs. If one wishes to write to more than one register, or to all 5, it is possible to issue all the WRITE to Register commands one after the other, and then follow them with a single Register Load Command.

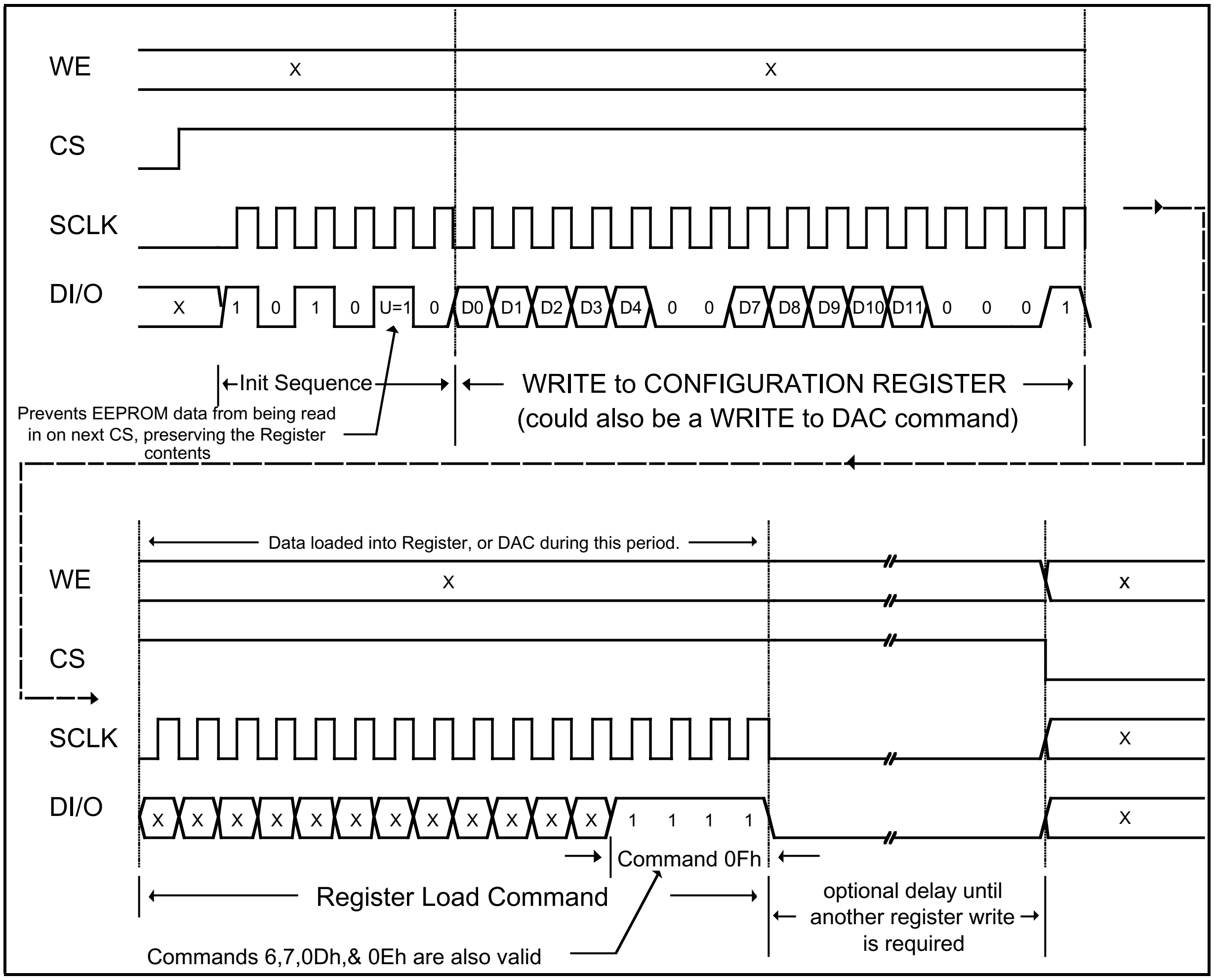


Figure 4-9

WRITE TO REGISTER Timing Diagram

MAX1478 MATHEMATICAL DESCRIPTION

The mathematical model will be based on a silicon piezoresistive pressure sensor, which will be compensated by the MAX1478 as a ratiometric output device. The equations can then be easily modified for other applications.

DEFINITION OF PARAMETERS

Before we begin deriving the system equations, it is necessary to first define some symbols and to state some assumptions.

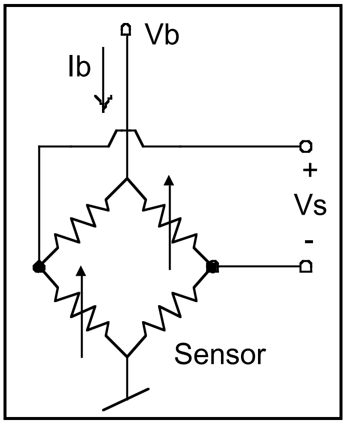


Figure 5-1

Sensor Electrical Model

Our sensor model will be that of a Silicon Piezoresistive Pressure Transducer (PRT) implemented as a four-wire closed Wheatstone bridge, as shown in Figure 5-1. At least one resistor element (an active resistor) will vary as a function of a mechanical excitation; it is not required that all resistors be active. Their resistance will also vary with temperature. The sensor-related parameters are defined as follows:

- Vb = Sensor excitation voltage
- Vs = Low-level differential sensor output normalized to its excitation voltage, Vb
- Sensor = The gross differential output of the sensor
- Ib = Sensor excitation current
- Rb = Sensor Bridge Impedance (Vb/Ib)
- T = Temperature, in °C
- P = Sensor mechanical excitation (pressure)
- S = Sensor mechanical excitation sensitivity
- Vof = Sensor offset per volt of bridge excitation

The ASIC-related parameters are defined as follows:

- VOUT = ASIC output voltage
- V_{SS} = ASIC negative supply
- V_{DD} = ASIC positive supply
- PGA = Signal Path (Programmable Gain Amplifier) gain
- ISRC = Current Source Reference Current
- AA = Current mirror gain (ratio)

The EEPROM-related parameters (coefficients) are:

- α = FSO coefficient (sets baseline excitation current)
- β = FSO TC coefficient
- γ = Offset coefficient (sets the zero pressure output)
- δ = Offset TC coefficient

And the key internal/external components are:

- Risrc = Resistor connected to pin ISRC and VSS (sets the current through the sensor)
- Rftc = FSO TC feedback resistor (sets the Ib temperature compensation)

It is important to notice that the EEPROM-related parameters are not actually the digitally stored values but normalized numbers ranging from 0 to 1. The offset and offset TC coefficients are bipolar; the FSO, FSOTC, and Linearity coefficients must always be positive.

EQUATIONS

The general sensor transfer function can be initially defined as:

$$Sensor = Vb \cdot \left(S \cdot P + Vof \right) + Misc$$

Equation 5-1

where:

- *Misc* = Represents all other error sources

The "Miscellaneous" errors are primarily non-repeatable and thus, since the ASIC is unable to correct these errors, will not be taken into account in subsequent equations. The equations will only model and address repeatable sensor behavior. Expanding the terms S, P, and Vof into higher-order dependency on temperature and pressure results in the following equation:

$$Vs = Vb \cdot \left[\left(s_0 + s_1 \cdot T + s_2 \cdot T^2 + (\ldots) \right) \cdot \left(e_0 + e_1 \cdot P + e_2 \cdot P^2 + (\ldots) \right) + \left(o_0 + o_1 \cdot T + o_2 \cdot T^2 + (\ldots) \right) \right]$$

Equation 5-2

where:

- s_N = Coefficients of sensitivity
- e_N = Coefficients of non-linearity excitation
- o_N = Coefficients of offset

A minimum of a second-order model of Equation 5-2 is usually required to describe the sensor behavior over temperature and pressure to better than 1% accuracy. The MAX1478 can compensate sensor errors over temperature and pressure to within 1% (typically) of the sensor's inherent repeatability. To achieve the full capability of the MAX1478's calibration accuracy, the sensor model may require second and third order components or higher. It is also important to note that there are many other error sources, including pressure and temperature hysteresis, non-repeatability, time-dependent behavior, etc. These parameters will not be modeled, since the ASIC can only correct ***repeatable*** sensor behavior. Thus the total compensated module accuracy will *never* be better than the total non-repeatability errors of the sensor, plus the ASIC/Test System compensation error.

We must also model the sensor bridge impedance as a function of temperature. It is assumed that *Rb* only changes with temperature. In some sensors, the bridge is intentionally designed to be slightly off-balance with pressure, to improve pressure linearity performance. The side effect of this in the MAX1478 circuit is that *Vb* will have a slight dependency on pressure. If this effect is present, it will usually be on the order of a few millivolts, and will typically correspond to a temperature equivalent error of just a few °C and can usually be ignored. If not, the equations must be modified accordingly. The bridge impedance can be described as:

$$Rb = r_0 + r_1 \cdot T + r_2 \cdot T^2 + (\ldots)$$

Equation 5-3

Referring to the MAX1478 block diagram in Figure 1-1, we can fundamentally divide the core analog section into two parts: the sensor excitation generator (Programmable Current Source) and the signal path amplifier (PGA). The fundamental part of the bridge excitation circuit is a programmable current source which is based around an FET pair current mirror, as shown in Figure 5-2.

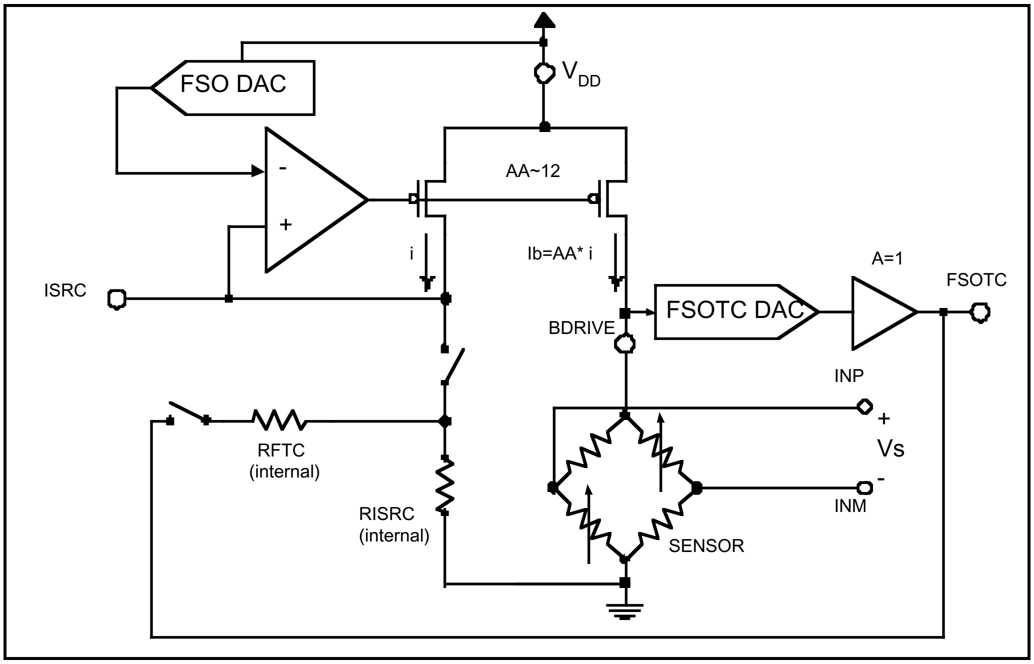


Figure 5-2

Bridge Drive Circuit

Any baseline current “i” flowing out of pin ISRC is gained up by a factor *AA*, the current source current mirror gain. The bridge baseline current is defined as:

$$Ib = AA \cdot i$$

Equation 5-4

The voltage across Risrc must be equal to FSODAC (as a result of the amplifier input virtual short-circuit), which can therefore can be used to set the baseline current through the bridge. The FSODAC output range is from V_{SS} to V_{DD}. This DAC therefore sets the baseline bridge excitation, which in turn programs the fine FSO of the module.

After substituting for “i” in Equation 5-4, the current through the bridge can be given by:

$$Ib = AA \cdot \left(\frac{FSODAC}{RISRC} \right)$$

Equation 5-5

and thus, assuming V_{SS} is equal to 0 volts:

$$Ib = AA \cdot \left(\frac{\alpha \cdot V_{DD}}{RISRC} \right)$$

Equation 5-6

and since $Ib = \frac{Vb}{Rb}$:

$$Vb = AA \cdot Rb \cdot \left(\frac{\alpha \cdot V_{DD}}{RISRC} \right)$$

Equation 5-7

The effect of Rftc has not been factored in yet. In the normal configuration, the “driven” side of Rftc is connected to FSOTCOUT. This is a buffer provided to drive this resistor with the output of the FSOTCDAC. This DAC takes the buffered bridge voltage, VBBUF, as its reference. In this way, any portion of the bridge voltage can be fed back to the current source control loop. Remembering that the bridge voltage will be proportional to temperature, this feedback path then becomes the FSO temperature compensation feedback, FSOTC. Adding this term into Equation 5-7 gives us:

$$Vb = AA \cdot Rb \cdot \left(\frac{\alpha \cdot V_{DD}}{RISRC} + \frac{\alpha \cdot V_{DD} - \beta \cdot Vb}{RFTC} \right)$$

Equation 5-8

and after solving Equation 5-8 for Vb explicitly, the bridge voltage is then given by:

$$Vb = V_{DD} \cdot \frac{\frac{\alpha}{RISRC} + \frac{\alpha}{RFTC}}{\frac{1}{AA \cdot Rb} + \frac{\beta}{RFTC}}$$

Equation 5-9

Current Source Excitation Voltage

The other analog section is the Signal Path Amplifier (PGA), whose block diagram is in shown in Figure 5-3.

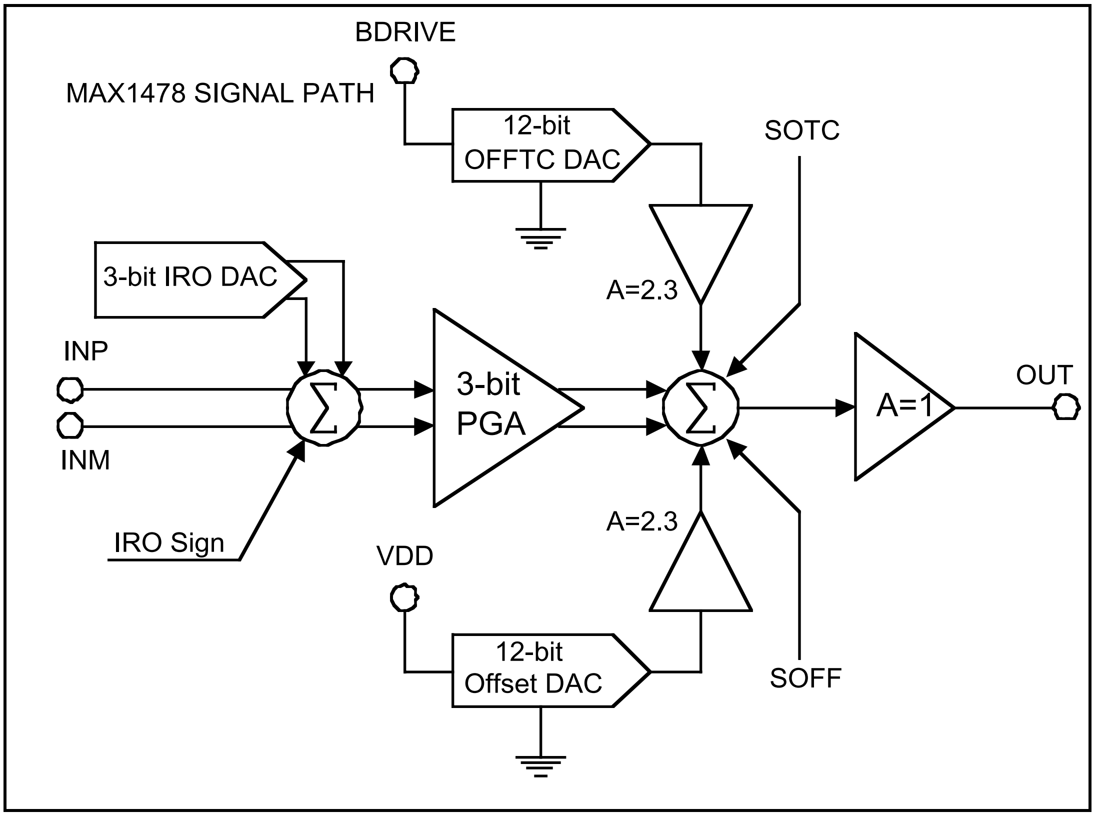


Figure 5-3

Signal Path Block Diagram

Both the sensor input and the IRO value are amplified by the PGA, so that the output can be given by:

$$VOUT = (INP - INM + IRO) \cdot PGA + OFFSET + OFFTC$$

Equation 5-10

By using their associated sign bits, the “OFFSET” and “OFFTC” corrections can be made bipolar and since the sensor output is:

$$Sensor = INP - INM$$

Equation 5-11

The MAX1478 output voltage can then be expressed as:

$$VOUT = (Sensor + IRO) \cdot PGA + OFFSET + OFFTC$$

Equation 5-12

PGA Transfer Function

The offset voltage is generated by the OFSTDAC. This DAC takes V_{SS} and V_{DD} as references. The state of the sign bit will become the sign of the coefficient, thus:

$$OFSTDAC = \gamma \cdot Vdd$$

Equation 5-13

Since the signal path is implemented using switched capacitor amplifiers, the numerical value of the apparent voltage at the "OFFSET" summing junction can actually be larger than V_{DD}. The offset TC correction is accomplished in terms of the OFFTCDAC. This DAC has its references as BDRIVE (which is actually Vb) and V_{SS}. The state of its sign bit will become the sign of the coefficient, and its output can then be expressed as:

$$OTCDAC = \delta \cdot Vb$$

Equation 5-14

OFFSET and OFFTC can then be expressed as:

$$OFFSET = 2.3 \cdot \gamma \cdot V_{DD}$$

Equation 5-15

$$OTC = 2.3 \cdot \delta \cdot Vb$$

Equation 5-16

The output voltage then becomes:

$$VOUT = (Sensor + IRO) \cdot PGA + 2.3 \cdot \gamma \cdot V_{DD} + 2.3 \cdot \delta \cdot Vb$$

Equation 5-17

This is a good time to summarize the 4 key equations that have been developed so far. Sensor is the gross, low-level output voltage of the sensor, as a function of bridge excitation voltage, pressure, and temperature. Rb is the sensor bridge input impedance as a function of temperature. Vb is the sensor excitation voltage generated by the MAX1478. Finally, VOUT is the output of the ASIC.

$$Sensor = Vb \cdot \left[\left(s_0 + s_1 \cdot T + s_2 \cdot T^2 + (\ldots) \right) \cdot \left(e_0 + e_1 \cdot P + e_2 \cdot P^2 + (\ldots) \right) + \left(o_0 + o_1 \cdot T + o_2 \cdot T^2 + (\ldots) \right) \right]$$

Equation 5-18

Differential Sensor Output Voltage

$$Rb = r_0 + r_1 \cdot T + r_2 \cdot T^2 + (\ldots)$$

Equation 5-19

Sensor Input Impedance

$$Vb = V_{DD} \cdot \frac{\dfrac{\alpha}{RISRC} + \dfrac{\alpha}{RFTC}}{\dfrac{1}{AA \cdot Rb} + \dfrac{\beta}{RFTC}}$$

Equation 5-20

Sensor Excitation Voltage

$$VOUT = (Sensor + IRO) \cdot PGA + 2.3 \cdot \gamma \cdot V_{DD} + 2.3 \cdot \delta \cdot Vb$$

Equation 5-21

Simplified MAX1478 Transfer Function

For simplicity, it is good to redefine Equation 5-18 as:

$$Sensor = Vb \cdot Vs$$

Equation 5-22

After substituting Equations 5-20 and 5-22 into Equation 5-21, and factoring the VOUT term, the transfer function of the MAX1478 can be expressed as:

$$VOUT = V_{DD} \cdot \left(\frac{\dfrac{\alpha}{RISRC} + \dfrac{\alpha}{RFTC}}{\dfrac{1}{AA \cdot Rb} + \dfrac{\beta}{RFTC}} \cdot \left[Vs \cdot PGA + 2.3 \cdot \delta \right] + IRO \cdot PGA + 2.3 \cdot \gamma \right)$$

Equation 5-23

MAX1478 Transfer Function Using Normalized Values

Equation 5-24 is the complete transfer function performed by the truly analog signal path of the MAX1478 (remembering that both the β and δ coefficients are temperature-dependent). To evaluate it, it is necessary to make the appropriate substitutions for *Rb* and Vs, which depend heavily on temperature, among other things. Whatever model is used for *Rb* and Vs, it *must* include temperature dependency, as in Equations 5-18 and 5-19.

Of the three main constituents in the numerator, the first is actually the "compensated" *Vb,* which includes the ASIC corrections for FSO TC and the linearity term. The sensor output is modulated by this "*Vb*" and gained up in the signal path by the PGA. The MAX1478 offset TC correction factor, which is a portion of the compensated "*Vb*", also appears in the numerator. The second term is the Coarse offset correction (IRO DAC) and the third term in the numerator shows that the final offset correction made at the last stage in the signal path is simply a ratio of V_{DD} and is independent of other variables. It is also often convenient to substitute our normalized DAC coefficients to obtain:

$$VOUT = V_{DD} \cdot \left(\frac{FSODAC \cdot \left(\frac{1}{RISRC} + \frac{1}{RFTC} \right)}{\frac{4095}{AA \cdot Rb} + \frac{FSOTCDAC}{RFTC}} \cdot \left[Vs \cdot PGA + 2.3 \cdot \frac{OFFTCDAC}{4095} \right] + \frac{IROCODE}{7 \cdot 80} \cdot PGA + 2.3 \cdot \frac{OFFSETDAC}{4095} \right)$$

Equation 5-24

MAX1478 Transfer Function

where:

- FSODAC = The 12-bit coefficient stored in the FSO DAC
- FSOTC = The 12-bit coefficient stored in the FSOTC DAC
- OFFTCDAC = The 12-bit coefficient stored in the OFFTC DAC multiplied by the OFFTC Sign bit
- OFFSETDAC = The 12-bit coefficient stored in the Offset DAC multiplied by the Offset Sign bit
- IROCODE = The 3-bit coefficient stored in the IRO DAC multiplied by the IRO Sign bit

SENSOR COMPENSATION THEORY

OVERVIEW

The MAX1478 is a high-performance monolithic sensor signal-conditioning integrated circuit intended for medium accuracy applications. The MAX1478 allows many degrees of freedom. Test algorithms can be implemented in many different ways. The final objective is always to produce a compensated module that meets the minimum specification objectives as inexpensively as possible.

It is initially assumed that the goal is to produce a compensated, pressure-sensing module using a silicon piezoresistive sensor (other sensor types are addressed later). It is assumed that we wish to produce a module that has a total accuracy better than ±1% over the automotive temperature range of -40 to +125°C.

The unique architecture of the MAX1478, along with its four 12-bit DACs, gives the ASIC the capability of compensating a PRT's repeatable errors to within ±1%. It must be stressed that the sum of all sensor non-repeatable errors and sensor temperature non-linearity errors will be the key factor limiting accuracy in a MAX1478-based transducer module. Thus, if the sensor exhibits a total error of ±0.5% (for non-repeatable behavior), we should add a minimum of ±1% for ASIC and test-system errors. Therefore, the total accuracy can not be expected to be better than ±1.5%.

By far, most of the compensation efforts will be focused on determining temperature-related coefficients. This is because the behavior is non-linear and not repeatable enough from part to part to the level that we require. Also, it may take an oven 1/2 hour or more to set a temperature and allow ample soaking time for the modules.

Most of the compensation effort will be in determining the temperature-related coefficients required to correct FSO and Offset errors. For the MAX1478, that means determining the values of the FSO Tempco (FSOTC) and the Offset TC (OTC) coefficients required for linear compensation.

INTRODUCTION TO ELECTRONIC SENSOR COMPENSATION

Traditional transducer designs perform the calibration and compensation in an analog domain. To store the sensor-specific data, analog "memory" components such as laser-trimmed resistors, potentiometers, and discrete resistors or capacitors (some of them temperature-dependent) are used. The major problems with such an approach include:

- Restricted accuracy of compensation, resulting from the non-linearity of sensor errors
- High cost of automated equipment such as laser trimmers
- Multiple setups are usually required for test and trim
- The number of components required prevent miniaturization

The emergence of low-cost digital programmable electronics opened the possibility for trimming analog functions in the digital domain, with a capability of storing individualized correction coefficients in nonvolatile digital memory (e.g., EEPROM). Such electronic trimming for sensors evolved into two generic approaches:

- Analog Sensor Signal Processors (ASSP) such as the MAX1450, MAX1457, MAX1458, MAX1459, and MAX1478, which adjust the Offset and gain of amplifiers, as well as the sensor excitation to achieve sensor calibration and temperature compensation in an analog domain, without signal quantization
- Digital Sensor Signal Processors (DSSP), such as the MAX1460, which convert the sensor signal into the digital domain using an A/D converter, perform calibration and compensation in a digital domain using a microcontroller or custom logic, and then (if needed), convert the signal into the analog domain via a DAC

Sensor Terminology

Figure 6-1 shows a typical pressure-sensor output and defines the Offset, full-scale (FS), and full-span-output (FSO) values as a function of the output voltage. Some sensor users may better know the FSO as the Span.

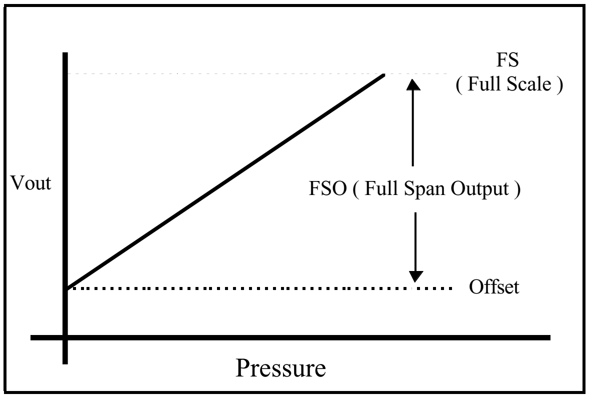


Figure 6-1

Definition of Sensor Terminology

The Basics of Electronic Trimming

Electronic trimming allows setting a specific analog function using digital memory instead of an analog memory. The key element of the electronic trimming system for the ASSP configuration is a digital-to-analog converter (DAC), which enables the multiplication of an analog voltage by a digital number
(Figure 6-2). The analog input voltage is multiplied by a digital number which generates an analog output voltage without having to convert it to the digital domain, preserving the analog transfer function and eliminating quantization errors.

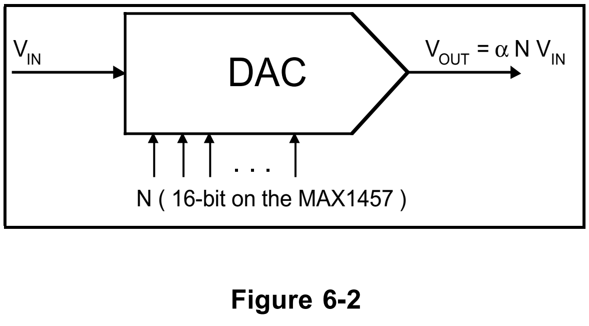


Figure 6-2

A DAC Used to Multiply an Analog Voltage, Vin, Without Converting It into the Digital Domain

A DAC requires an input (or reference) voltage *Vin* and generates an output voltage *Vout* that is the product of the input voltage, a calibration constant α, and a digital number *N* (which is 12 bits for the MAX1478):

$$Vout = \alpha\, N\, Vin$$

The digital number *N* can be stored in memory, enabling the customization of the electronic performance of each sensor, thus forming the foundation of programmable electronic trimming. To enable low-cost applications, Maxim Integrated Products, Inc. developed a unique DAC circuit topology, which yields 12-bit performance while fitting on a very small area of silicon. The small size of such converters enables cost-efficient implementation of the complex systems-on-a-chip (such as the MAX1478) which require multiple high-resolution DACs.

Electronic Trimming with the MAX1478

Multiple configuration DACs are used for the compensation and calibration functions within the MAX1478. Four 12-bit DACs are used for the following functions:

- Initial Offset calibration (OFSTDAC)
- Initial FSO calibration (FSODAC)
- Offset TC compensation (OTCDAC)
- FSO TC compensation (FSOTCDAC)

The initial Offset correction is implemented in two ways. First, a front-end coarse offset correction can be made, before the signal is amplified by the PGA, to increase the dynamic range of the signal path. The IRO DAC is used for this purpose; it is a 3-bit DAC, plus sign, which takes its reference as 1/80 of the supply Vdd. This gives an input-referred adjustable offset range of ± 63mV, assuming a supply of 5 Volts. Second, a fine output-referred offset adjustment is made by multiplying a fraction of the supply voltage *Vdd* by a 12-bit word (OFSTDAC) to create a voltage that feeds into the summing junction of the PGA (Programmable Gain Amplifier), thereby calibrating the sensor Offset.

The FSO calibration is achieved using two adjustments. The coarse FSO range is set by adjusting the gain of the PGA with 3 bits of resolution; in this case, Vin is the sensor signal (INP-INM) which is multiplied by a digital word. The second component of the calibration is a fine adjustment of the sensor bridge excitation current using a 12-bit word (FSODAC). To achieve compensation of the linear component of the Offset and FSO temperature errors, the reference inputs of two DACs (OTCDAC and FSOTCDAC, respectively) are connected to the bridge voltage *Vb*. Thus, for any fixed digital word (temperature compensation coefficient), the DAC's output voltage will follow the bridge voltage as it changes (quasi-linear) with temperature. By adjusting the coefficient, compensation of the temperature slope is achieved.

THE SENSOR

The MAX1478 is specifically designed with silicon piezoresistive sensors in mind. It uniquely exploits certain characteristics of this type of sensor to maximize the module accuracy, minimize cost, and minimize module size by integrating as much of the specific circuitry as possible inside. Other sensor types may also be compensated with the MAX1478, but they may require additional circuitry (other sensor types are covered later). Throughout this chapter, we will make specific reference to pressure sensors (because they are most prevalent); however, our discussions could also apply to other types of sensors as well, such as accelerometers, etc.

The sensor should be comprised of a closed Wheatstone bridge arrangement. In this arrangement, diagonally opposing legs of the sensor vary equally and in the same direction as a function of mechanical excitation. Thus, the sensor's input impedance should not change as a function of mechanical excitation; we will show later that any change in the sensor input impedance will be interpreted by the MAX1478 as a change in temperature.

The MAX1478 relies on and exploits the fact that the sensor bridge input impedance varies greatly with temperature. With the proper sensor excitation techniques, one can effectively convert the pressure-sensor element into a temperature sensor. The key advantage of this method of sensing temperature is that it is done at the sensor diaphragm itself, providing excellent temperature response with virtually no thermal latency errors.

For reasons that will become clear later, the MAX1478 relies on the fact that the sensor bridge input impedance temperature coefficient (TCR) is large and that the magnitude of TCR is larger than the magnitude of the sensitivity temperature coefficient (TCS). Also for reasons that will become clear later, the sensor Offset temperature coefficient (OTC) must not be larger in magnitude than about 1.5 times that of TCS, when both are expressed as a percentage of FSO. With a sensor having a nominal input impedance of about 5K Ohms at room temperature, the ideal sensor excitation current will be about 500µA for an excitation voltage of 2.5 volts.

Some sensors are designed so that their characteristics can be altered by adding external components. In most cases, these components should not be used and the sensor should be left configured as a simple, four-resistor Wheatstone bridge. Provisions are sometimes made where the bridge can be split in various ways in order to add external resistors to correct parameters such as gross Offset error, FSO error, etc. These compensation efforts are usually unable to correct sensor errors very precisely, leaving the need for electronic signal conditioning to complete the task for more precise applications. Unless the sensor has gross errors beyond the capability of the MAX1478, we recommend using bare sensor elements with the MAX1478. This saves cost and the time of compensation redundancy. Some sensors contain additional resistive elements to aid in "OP-AMP"-based compensation schemes. Generally, these additional elements are not required with the MAX1478.

Silicon Piezoresistive Sensors

By far, most silicon piezoresistive sensors being manufactured today are for pressure-sensing applications. These sensors are almost always arranged as a four-resistor Wheatstone bridge on a single monolithic DIE (Bulk Micromachining). The sensors are inexpensive because they are processed on a wafer (which may contain from a few hundred to a few thousand sensing elements), much like integrated circuits. The major use of this type of sensor thus far has been for low-to-medium accuracy applications in automotive and consumer markets and for some industrial applications. The sensor's nonlinear errors over temperature have been one limiting factor in their being able to penetrate the higher-end markets currently being addressed by strain gauge elements and others, despite the fact that these other sensors are significantly more expensive.

Manufacturers all have their own "formula" for making PRTs and, as a result, there is wide variety in sensor performance and behavior. One of the most important parameters is TCR. The MAX1478 is optimized for use with sensors designed for current mode operation, which have a TCR in the neighborhood of 2000 ppm/°C or more. Voltage mode excitation sensors have a characteristically low TCR, which may necessitate the addition of more external circuitry to the MAX1478. It is preferred that TCR be greater than TCS in magnitude; they must always be opposite in polarity, with TCS decreasing with increasing temperature. The ideal sensor used with the MAX1478 will not change input impedance as a function of mechanical excitation (pressure). PRTs which are misbalanced, either intentionally (to optimize FSO linearity) or unintentionally, may behave poorly with the MAX1478.

Table 6-1 is an arguable list of typical errors found in an untrimmed silicon piezoresistive pressure sensor die over a wide temperature range. TC1 refers to first-order errors of temperature and TC2 refers to second-order errors of temperature. The automotive temperature is assumed (-40 to +125°C) using bare sensor DIE with no trimming resistors. These figures are arguable, depending on the sensor manufacturer, but they are good first-order estimates.

Error type	***Error***
Offset	±25 % FSO
Offset TC1	±10 % FSO
Offset TC2	±1 % FSO
FSO linearity	< ±0.1 % FSO
FSO TC1, voltage mode	35 % FSO
FSO TC1: current mode	3 % FSO
FSO TC2	1 % FSO
Misc. errors (no oil)	±0.2% FSO
Misc. errors (oil filled)	±0.75% FSO
I/O impedance TC1	38 % FSO (2300 ppm)
I/O impedance TC2	1 % FSO
TYP gain error	100

Table 6-1

Characteristics of a Typical Silicon Piezoresistive Sensor

One objective of the module design should be to minimize the number of parameters to be trimmed. The design should also minimize the number of parameters that must be trimmed on a part-to-part basis, particularly those that involve temperature. Sometimes it is possible to sacrifice one parameter for another. For example, one could select a sensor with lower sensitivity than required (i.e., of higher operating pressure) in order to minimize or eliminate pressure linearity trimming. The tradeoff might be that the Offset and Offset TC errors may be aggravated, perhaps noise and some “Misc.” errors would increase somewhat, since more signal path gain would be required.

LINEAR COMPENSATION

GENERAL

The MAX1478 contains two 12-bit DACs for correcting FSO TC and Offset TC errors. A single FSO TC and a single Offset TC coefficient is used throughout the temperature band to correct the sensor errors. We refer to this mode of compensation as “Linear compensation”. It is not purely linear, but it is a close approximation. The compensation is purely analog (continuous); i.e. no quantization noise.

The MAX1478 corrects FSO TC errors in a very different manner from Offset TC errors. Nevertheless, both errors are corrected in a purely analog (continuous) fashion. Since the Offset TC correction cannot be performed until the FSO TC correction is done, we will first discuss the method for performing FSO TC error compensation.

FSO TC COMPENSATION

Compensating FSO TC errors with the MAX1478 is fundamentally accomplished by forcing the sensor excitation voltage Vb to increase with temperature at the same rate that the sensor sensitivity decreases with temperature. The TCS of the sensor will be inherently fixed by design and cannot be altered. Therefore, if we wish to compensate FSO TC errors, we are forced to modulate the sensor excitation voltage accordingly, which in effect places the sensor excitation voltage Vb at the mercy of TCS. We begin with a near-perfect current source (for our purposes, one that does not exhibit a large Tempco), which implies that Vb will essentially track TCR, which is positive and typically larger in magnitude than TCS. As a result (in the absence of Rftc), Vb will tend to increase (with temperature) faster than the TCS falls off. This implies that (with a perfect current source) the sensor will exhibit a positive FSO TC residual, with a magnitude which will be representative of the difference between TCR and TCS (Figure 7-1). The remaining FSO TC error can then be eliminated by adding an appropriate negative TC error to the current source, accomplished by Rftc.

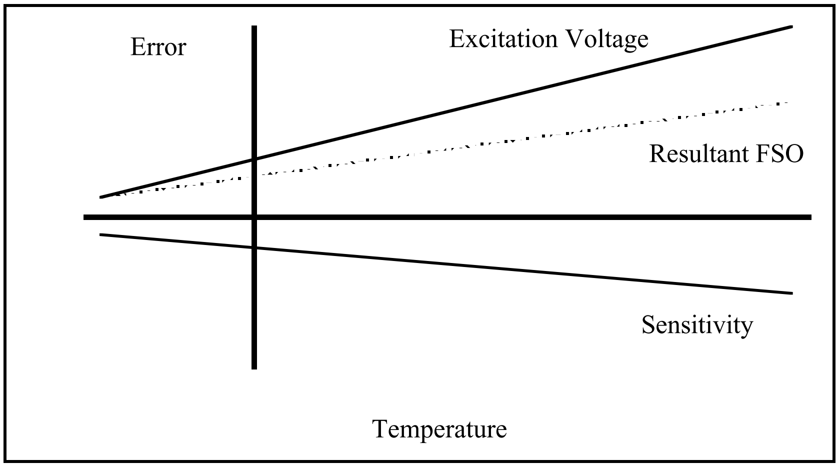


Figure 7-1

FSO of a Silicon PRT Under Constant Current Excitation

Since the MAX1478 excites the sensor with constant current, Vb (the sensor excitation voltage) should also vary with temperature, because Rb (the sensor input impedance) also varies with temperature. Since $Vb = Ib * Rb$, the excitation voltage Vb will increase with temperature as a result of Rb increasing with temperature. The output voltage (FSO) of the sensor is proportional to Vb. We can then conclude that if the sensor sensitivity does not change with temperature, the sensor FSO should increase with temperature. However, silicon PRTs will typically exhibit a decrease in sensitivity as temperature increases. For most sensors, the magnitude of this change is less than the change in TCR. As a result, under constant current excitation, most silicon PRTs will have a positive uncompensated FSO TC error (Figure 7-1). An ideal TCR would be equal in magnitude to TCS and opposite in polarity. This would offer us a complete cancellation of thermal effects when driven with a perfect current source and, as a result, our FSO would not vary with temperature (no FSO TC).

Sensor manufacturers often try to optimize their process parameters so that they can produce a sensor which has a TCR equal in magnitude and opposite in polarity to TCS, thus eliminating FSO TC errors by design. These efforts usually reduce FSO TC errors to a few percent in constant current mode, but it is beyond the ability of the sensor manufacturer to control the process variables tightly enough to improve this error margin any further.

In the absence of TCR being the perfect complement to TCS, we can in effect “modulate” the excitation to make it behave as the complement of TCS. This is the method employed by the MAX1478 (Figure 7-2). The programmable current source employs a feedback system that can reduce (rotate clockwise) the slope of the excitation voltage, Vb, until it is equal in magnitude (and opposite in polarity) to TCS. This is called the FSO TC compensation, which is in principle the alteration of the current source Tempco. Since the feedback loop can only decrease the TC of the current source, it becomes evident why the MAX1478 requires that the sensor’s TCR always be larger in magnitude than TCS (later we will discuss ways to get around this requirement). Lastly, a more detailed analysis of the equation for Vb would reveal that the FSO TC correction (rotation of TC) is not purely linear, but does represent a fairly good approximation. A real PRT sensor does not exhibit purely linear (first-order) errors, however. A characteristic behavior of a PRT would be some residual higher-order error as well. The sensitivity is usually convex, necessitating a more powerful method of forcing TCR to appear as the exact mirror opposite of TCS if higher compensation accuracy is required. This type of compensation (vector table piece-wise compensation) is addressed by the MAX1457, which is an enhanced version of the MAX1478.

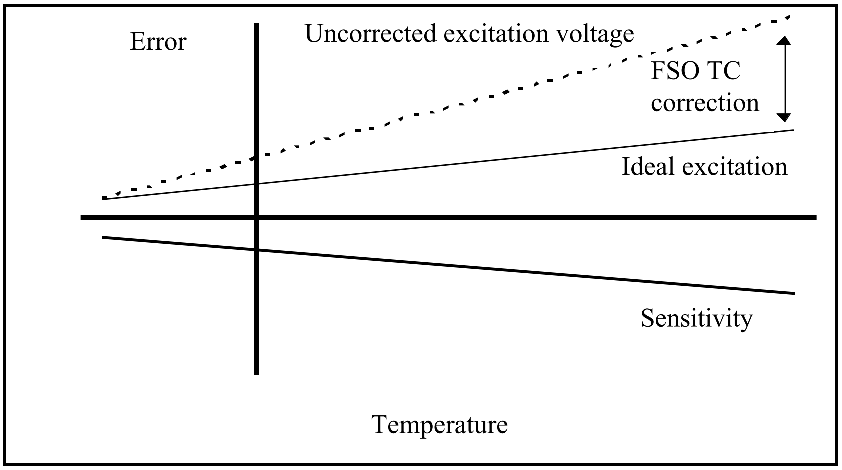


Figure 7-2

Effect of FSO TC Corrections on Sensor Excitation Voltage, Vb

Close inspection of Figure 7-2 will also reveal that the point of rotation of the TCR curve lies far to the left on the temperature scale. For silicon PRTs, it will always lie far beyond the coldest temperature point that we would use to compensate the device (normal operating temperature region). As a result, adjusting the FSO TC at one temperature point will always affect all other temperature points; the adjustment is non-orthogonal. Any change to the FSO TC coefficient will also affect the FSO, and will thus require a readjustment of the sensor excitation voltage (FSO coefficient) to restore our desired FSO. Because of this interaction, it is important to understand there can only be one unique pair of coefficients (FSO TC and FSO) that can perfectly compensate the sensor first-order errors and give the perfect FSO desired at the two temperature points we wish to use; this will be explained later. We will make a closer examination of the MAX1478's transfer function for Vb, to show that once FSO TC is compensated, we are free to readjust the FSO coefficient without disturbing the FSO TC calibration.

Once we understand there are interactions between the FSO and the FSO TC coefficients, we can see that to compensate FSO, we must set up a system of two linear equations and solve them simultaneously. Previously, in the section covering the MAX1478 equations, we derived symbolic solutions for our ideal FSO-related coefficients. They were exact symbolic solutions, however; putting them to practical use requires many parameters, including the bridge input impedance at two temperatures. Since ultimately we wish to produce a transducer with a total accuracy within 1% of the sensor repeatability limitations, we would also need to know the values of these coefficients to within that degree of accuracy or better. The manner in which the equations were derived assumed variables such as resistors did not vary with temperature. In fact, a typical surface-mount resistor with a TC of +/- 100 ppm/°C will vary +/- 1.65% over the automotive temperature range, an amount that we could not ignore. These reasons force us to look for a simpler, more robust solution for the calculation of the FSO and FSO TC coefficients which requires little specific circuit knowledge. If we refer to Equation 5-10, we can express the sensor excitation voltage as:

$$Vb = \alpha \cdot Vdd \cdot \frac{\frac{1}{Risrc} \cdot \frac{1}{Rstc}}{\frac{1}{AA \cdot Rb} + \frac{\beta}{Rstc}}$$

Equation 7-1

Looking at the Equation 7-1, we should see that at any given temperature, the values of Risrc, Rftc, AA, Rb, and Vdd must be constant and unique to that temperature. Thus, a simpler model can be established which still reasonably preserves our transfer function as:

$$Vb = \frac{\alpha \cdot k1}{1 + \frac{\beta}{k2}}$$

Equation 7-2

At each temperature, there is only one unique value of Vb that will generate our ideal FSO. Our FSO will be a linear function of Vb (assuming that the sensor has no voltage coefficient). With this in mind, we can always determine our ideal Vb by measuring the FSO with an arbitrary value for Vb and then ratioing Vb according to the newly measured FSO error.

Example:

At a given temperature, we chose an arbitrary (preferably a low estimate to avoid saturating the MAX1478) excitation voltage of 2 volts. We then measure the module FSO which is $Vout(P\max) - Vout(P\min)$. We must assure the MAX1478 does not reach output saturation during these measurements. We can then determine the ideal Vb at that particular temperature as:

$$Vb(ideal) = Vb(uncompensated) \cdot \frac{idealspan}{Vout(P\max) - Vout(P\min)}$$

Equation 7-3

In some cases, it may not be possible to use Equation 7-3 because the output may saturate. If this is the case, we must use a reduced test pressure, Pmax. This will necessitate modifying our equation to account for the lower input pressure as follows:

$$Vb(ideal) = Vb(uncompensated)\,\frac{idealspan}{Vout(P\max) - Vout(P\min)\cdot\dfrac{idealpressure}{actualtestpressure}}$$

Equation 7-4

Now we have found our ideal Vb, we are left with one equation and two unknowns: k1 and k2. We can now determine the values of k1 and k2 by empirically choosing two αs and two βs (two equations with two unknowns) that will yield our ideal Vb. We should also assign α and β numerical values ranging from 0 to 4095 to produce constants k1 and k2 that directly generate the number to be stored in the FSO and FSO TC registers. At any given temperature and value for Vb, there will be an infinite number of pairs of αs and βs that will satisfy our equation, but there will only be one pair that will satisfy two equations (at two different temperature points) simultaneously. We begin by setting up two equations for Vb at the same temperature:

$$Vb = \frac{\alpha 1\cdot k1}{1+\dfrac{\beta 1}{k2}} \qquad \text{and} \qquad Vb = \frac{\alpha 2\cdot k1}{1+\dfrac{\beta 2}{k2}}$$

Where $\alpha 1 \neq \alpha 2$, and $\beta 1 \neq \beta 2$. Next, we solve for k1 and k2.

$$k1 = Vb\cdot\frac{\beta 2-\beta 1}{\beta 2\cdot\alpha 1-\alpha 2\cdot\beta 1} \qquad \text{and} \qquad k2 = \frac{\beta 2\cdot\alpha 1-\alpha 2\cdot\beta 1}{\alpha 2-\alpha 1}$$

Lastly, we make the appropriate substitution for k1 and k2 as:

$$Vb = \frac{\alpha\cdot\dfrac{\beta 2-\beta 1}{\beta 2\cdot\alpha 1-\alpha 2\cdot\beta 1}}{1+\dfrac{\beta}{\dfrac{\beta 2\cdot\alpha 1-\alpha 2\cdot\beta 1}{\alpha 2-\alpha 1}}}$$

Equation 7-5

Sensor Excitation Voltage Dependency on α and β

To summarize, Equation 7-5 provides us with a way to model Vb as a function of the FSO and FSO TC coefficients. The principal advantage of this method of computing the coefficients is that the effect of all the variables in our general equation for Vb (Risrc, Rftc, Rb(t), etc.) is being accurately modeled without our having to know their exact values. Of course, this model is very constrained, and **will only work for the unique Vb for which it was derived**. It will also only work **at the unique temperature at which it was derived**.

With Equation 7-5, we can generate an infinite number of pairs of αs and βs that will give us the desired Vb at a unique temperature. Unfortunately, at any other temperature, we would require a different set of FSO and FSO TC coefficients. However, we know there is one unique α and β that will satisfy the linear compensation of FSO and FSO TC at two temperature points.

To complete our solution for unique values of α and β that will satisfy two equations at two different temperatures, and with a different value of Vb at each temperature, we must set up a system of two equations of the form in Equation 7-5 for each of two temperatures. We will refer to these two temperatures as temperature “C” for cold and temperature “H” for hot, and append the coefficients accordingly.

$$VbC = \frac{\alpha \cdot \dfrac{\beta 2C - \beta 1C}{\beta 2C \cdot \alpha 1C - \alpha 2C \cdot \beta 1C}}{1 + \dfrac{\dfrac{\beta}{\beta 2C \cdot \alpha 1C - \alpha 2C \cdot \beta 1C}}{\alpha 2C - \alpha 1C}} \qquad VbH = \frac{\alpha \cdot \dfrac{\beta 2H - \beta 1H}{\beta 2H \cdot \alpha 1H - \alpha 2H \cdot \beta 1H}}{1 + \dfrac{\dfrac{\beta}{\beta 2H \cdot \alpha 1H - \alpha 2H \cdot \beta 1H}}{\alpha 2H - \alpha 1H}}$$

Equation 7-6 **Equation 7-7**

Simultaneous Equation Pair for Vb at Two Test Temperatures

Finally, we can solve for α and β explicitly. It requires quite a bit of algebraic reduction to express them in the form below. Again, variables ending with "C" refer to the first temperature point (cold), and variables ending with "H" refer to the second temperature point (hot).

$$denomenator = \beta 1H \cdot (\alpha 2C - \alpha 1C) + \beta 2C \cdot (\alpha 2H - \alpha 1H) + \beta 2H \cdot (\alpha 1C - \alpha 2C) + \beta 1C \cdot (\alpha 1H - \alpha 2H)$$

Equation 7-8

$$\alpha = \frac{\alpha 1H \cdot (\beta 2H \cdot \alpha 1C - \beta 2H \cdot \alpha 2C + \beta 1C \cdot \alpha 2C - \alpha 1C \cdot \beta 2C) + \alpha 2H \cdot (\beta 1H \cdot \alpha 2C - \beta 1C \cdot \alpha 2C + \alpha 1C \cdot \beta 2C - \beta 1H \cdot \alpha 1C)}{denomenator}$$

Equation 7-9

Solution for FSO Coefficient

$$\beta = \frac{\beta 2C \cdot (\beta 1H \cdot \alpha 2H - \beta 2H \cdot \alpha 1H + \alpha 1C \cdot \beta 2H - \alpha 1C \cdot \beta 1H) + \beta 1C \cdot (\beta 2H \cdot \alpha 1H - \alpha 2C \cdot \beta 2H + \alpha 2C \cdot \beta 1H - \beta 1H \cdot \alpha 2H)}{denomenator}$$

Equation 7-10

Solution for FSO TC Coefficient

After setting the FSO and FSO TC coefficients to the values of α and β as determined by Equations 7-9, and 7-10, respectively, we will have forced Vb's TC slope to be the linear mirror image of TCS and thus the first-order FSO TC errors are now compensated. The FSO will also be compensated.

Example:

We wish to compensate our sensor from -40 to +125°C. Using Equations 7-3 or 7-4, we determined the following sensor specific ideal Vb at the two temperature extremes:

$$VbC = 2.5 \qquad VbH = 3.5$$

At -40°C, we arbitrarily selected a β1C of 2048 (0800h) and found that we needed to set α1C to a value of 1432 to attain our ideal value of VbC. We then changed our FSO TC coefficient to an arbitrary number of 1792 (0700h); this will be β2C. We then again adjusted the FSO coefficient until we set Vb back to the value of VbC. This second FSO coefficient will be α2C. We then repeat all of these steps again at +125 °C to arrive at the following set of values:

at -40 °C $VbC = 2.5$ at +125 °C $VbH = 3.5$

$\alpha 1C = 1432$ $\beta 1C = 2048$ $\alpha 1H = 1737$ $\beta 1H = 2304$

$\alpha 2C = 1371 \quad \beta 2C = 1792 \qquad\qquad \alpha 2H = 1569 \quad \beta 2H = 2560$

Now using Equations 7-8, 7-9, and 7-10 gives us the solutions:

$\alpha = 1557$ FSO coefficient
$\beta = 2576$ FSO TC coefficient

Equations 7-8, 7-9, and 7-10 are expressed in general form which provides the most freedom for selecting optimal coefficient pairs (prevent MAX1478 saturation, yield best accuracy, etc.) for the specific sensor being used. However, if a few constraints are placed on the coefficient pairs, the algebra can be reduced considerably. We accomplish this by equating β1C to β1H and β2C to β2H. This reduces Equations 7-8, 7-9, and 7-10 to:

$$\beta = \frac{\beta 1 * \alpha 2H + \beta 2 * \alpha 1C - \beta 1 * \alpha 2C - \beta 2 * \alpha 1H}{\alpha 2H + \alpha 1C - \alpha 1H - \alpha 2C}$$

Equation 7-11

Simplified Solution for the FSO Coefficient

$$\alpha = \frac{\alpha 2H * \alpha 1C - \alpha 1H * \alpha 2C}{\alpha 2H + \alpha 1C - \alpha 1H - \alpha 2C}$$

Equation 7-12

Simplified Solution for the FSO TC Coefficient

Although the equations above were derived based on formulas that only approximate the exact transfer function of the MAX1478, they will typically yield a result which is less than 1% in error. We should point out that without regard to α, the single value for β we derived uniquely sets the FSO TC correction. Another way to express this is to say the value of β sets up our FSO TC feedback loop so the change in Vb over temperature divided by the magnitude of Vb remains a constant as we adjust the FSO. The FSO TC error will remain compensated regardless of any change we now make to α to readjust the FSO.

To further explain this phenomenon, look again at the example above. At -40°C, our ideal sensor excitation voltage must be $VbC = 2.5$ to attain our desired FSO; at +125°C, our ideal excitation voltage must be $VbH = 3.5$. The ratio of VbH to VbC indicates we need 40% more excitation voltage at +125°C than we need at -40°C. This implies our sensor's sensitivity drops by 40% at +125°C with respect to -40°C.

Equation 5-10 for Vb shows that Vb is directly proportional to the value of α, the FSO coefficient. Thus if we double the value of α, the sensor excitation voltage will double at every temperature and so will our FSO. Our new VbC will increase to 5 volts and our new VbH will increase to 7 volts. The increase in Vb's value over temperature is still 40%, thereby preserving our FSO TC compensation. This will remain true so long as our sensor does not have a voltage coefficient; that is, so long as the normalized sensitivity is not a function of the sensor's excitation voltage. This is true for most silicon PRTs, at least to the degree of accuracy we may wish to address with the MAX1478, which will be primarily limited by the inherent sensor repeatability errors.

When using the Equations 7-8 through 7-12, α is only valid if β is valid; α should be considered dependent on β. It is possible to generate βs which are larger than the size of our DAC with these equations; that is, >4095. When this occurs, it is an indication the value chosen for Rftc is too large and we have insufficient feedback in our current source. The solution is to decrease the value of Rftc. A value of β which is negative is usually an indication the sensor's TCR is less in magnitude than its TCS, which is a violation of the MAX1478 sensor requirements. If the coefficient is a low number, the value of Rftc is too low and there is a danger the FSOTC buffer will be near low-side saturation (refer to the data sheet). Refer to a later discussion on this subject for alternative circuit solutions for these sensors.

OFFSET TC COMPENSATION

After compensating FSO TC, we have placed Vb at the mercy of TCS. Regardless of how Vb (Rb) wanted to behave as a function of temperature, we have altered this behavior by modulating the current source to suit the needs of the sensor's sensitivity behavior over temperature (TCS). In effect, we begin with a perfect current source and intentionally distort its temperature response to correct for TCS errors. Except in the case where the sensor has no TCS, Vb should now vary with temperature in a fairly linear and predictable manner. The slope of this variation must be the inverse of TCS. We can now take an appropriate portion of this voltage Vb and use it as an analog voltage which varies with temperature to correct our Offset TC error at the signal path-summing junction.

We have explained how Vb(t) is at the mercy of TCS. Now we must explain why the Offset TC is also placed at the mercy of TCS. We must distort the shape of Vb (by modulating the current source with temperature) to conform to the inverse shape of TCS. However, since we are using a ratio of the excitation voltage Vb to correct our Offset TC errors, we can see, to one extent or another, a portion of these distortions in Vb will also be introduced into the signal path via the Offset TC summing junction. These distortions are usually small.

An uncompensated MAX1478-based module will exhibit a deviation of the output voltage at minimum pressure as a function of temperature. This error is defined as an Offset TC (Offset Temperature Coefficient) error. Although this error is due to many factors within a sensor module, including the sensor signal conditioning electronics, it is primarily a function the sensor errors which the MAX1478 is expected to correct.

On MAX1478-based products, the source of this error (within the module) is unimportant so long as it is repeatable and within the trimming limitations of the MAX1478, which will be limited to about 1.5 times the magnitude of the uncorrected sensor FSO TC error. Because of this, it is preferred to treat the pressure sensor module, which includes the sensor and all other electronic components, as a black box which has temperature as an input and voltage as an output at some specific fixed (reference) pressure.

We can think of our black box as having a second input signal that varies with temperature at the same rate as our uncorrected output error, the same magnitude as the Offset TC error, but with an opposite slope or polarity. The Offset TC sign bit can be used to insure the correction voltage is always opposite in sign to the uncompensated Offset error over temperature.

An Offset TC error materializes as a voltage drift or a continuous and repeatable variation in the output voltage as temperature is changed. This error is primarily linear and usually contains a few percent of residual higher-order errors. As mentioned before, if we introduce a voltage into the signal path summing junction which varies with temperature at the same rate as our Offset error, but is opposite in polarity, we would in effect null this error at the output of the MAX1478 and the only errors remaining would be a very few percent of higher-order Offset TC errors.

Vb offers an almost ideal temperature-dependent voltage, since it tracks the actual temperature of the sensor diaphragm. This unique feature of the MAX1478 architecture offers superior temperature tracking over other compensation methods employing a remote temperature sensor, which may be thermally distant from the media, and the sensor element where the temperature sensing would be ideally desired. The MAX1478 does give the user the flexibility of using an external temperature sensor.

Linear Offset TC compensation of a MAX1478-based product is fundamentally based on determining what ratio of the change in Vb over temperature must be added into the OTC summing junction of the signal path to perfectly remove the linear or first-order Offset TC error of the module. Before proceeding, it is mandatory to perform the FSO TC calibration of the module before the Offset TC can be corrected, because the correction of the Offset TC error requires knowing the exact ideal sensor excitation voltage at the two temperatures and the exact uncompensated error in the Offset over temperature. The compensated Offset TC must satisfy the following relationship:

$$uncompensatedOffsetError + correction = 0$$

Equation 7-13

where:

"uncompensated Offset error" is the change in the module output voltage over temperature based on the two ideal Vb’s at the two temperature extremes.

"correction" is a temperature-varying voltage introduced at the summing junction. This can then be expressed as:

$$(VoutH - VoutC) + (OFFTC \cdot (VbH - VbC)) = 0$$

Equation 7-14

where:

"VoutC" is the uncompensated output voltage at temperature “C” with the sensor excitation voltage set to VbC which is the IDEAL Vb giving the perfect FSO at temperature “C”.

"VoutH" is the uncompensated output voltage at temperature “H” with the sensor excitation voltage set to VbH which is the IDEAL Vb giving the perfect FSO at temperature “H”.

"VbC" is the IDEAL Vb at temperature “C”.

"VbH” is the IDEAL Vb at temperature “H”.

"OFFTC" is the normalized correction coefficient.

If Equation 7-14 is solved for the correction coefficient "OTC":

$$OFFTC = \frac{VoutC - VoutH}{VbH - VbC}$$

Equation 7-15

Next, recall that this correction voltage presented at the Offset TC summing junction of the signal path will be gained up by a factor of 2.3. This gain was added to the MAX1478 to extend the Offset TC compensation range and will further reduce the value of the coefficient "OFFTC". Also, the coefficient must be expressed as a numerical value that can be loaded into the Offset TC DAC, thus:

$$OFFTCcode = OFFTCDACrange \cdot \frac{OFFTC}{OFFTCgain}$$

Equation 7-16

where:

"OFFTCgain" is the gain through the summing junction. This is expressed as the summing junction gain multiplied by the Offset TC DAC gain.

"OFFTCDACrange" is the full-scale numerical code for the Offset TC DAC (4095).

Then, combining the two Equations 7-15 and 7-16:

$$OFFTCcode = \frac{OFFTCDACrange \cdot (VoutC - VoutH)}{OFFTCgain \cdot (VbH - VbC)}$$

Equation 7-17

OFFTCgain, the signal gain at the input of the signal path-summing junction, can be determined empirically, provided that the OFFTCcode is temporarily set to full scale. In essence, change the bridge excitation voltage and measure the effect that appears at the output (Vout) as a result. This value will be about 2.3 and is essentially insensitive to temperature effects.

$$OFFTCgain = \frac{\Delta Vout}{\Delta Vb} - SensorEffect$$

Equation 7-18

where:

ΔVout is the measured change in the output voltage at pin Vout under maximum Offset TC gain.

ΔVb is the change in the sensor excitation voltage which we intentionally cause as a result of temporarily altering the FSO DAC code.

Substituting the numerical equivalents for OFFTCDACrange and OFFTCgain to arrive at the final solution:

$$OFFTCcode = \frac{4095 \cdot (VoutC - VoutH)}{2.3 \cdot (VbH - VbC)}$$

Equation 7-19

Offset TC Correction

It is very important to note that "OFFTCcode" represents the SIGNED numerical CHANGE required to the current Offset TC coefficient loaded at the time that the Offset TC error was measured. Thus, it is not mandatory that the Offset TC be shut off (but it must not be changed during the tests); i.e., the Offset TC coefficient is equal to 0. This is significant because in a sensor with very large Offset TC errors, the uncompensated module output voltage may saturate as temperature is changed. If some general knowledge of the MEAN Offset TC behavior for the sensor family is known, however, then initialization coefficients can be loaded into the Offset TC register to minimize the initial uncalibrated errors. If the Offset TC coefficient was not set to 0, it is important to understand that it should not have been changed during the time in which the above measurements were made. If the initial Offset TC code was 0, then OFFTCcode does indeed represent the actual numerical coefficient which is to be loaded into the Offset TC register, and the SIGN of OFFTCcode will represent the sign of the OFFTCsign bit.

Example 1:

VoutC = 0.75; VoutH = 1.25; VbC = 2.0; VbH = 3.0; OFFTCcode=0

$$OFFTCcode = \frac{4095 \cdot (0.75 - 1.25)}{2.3 \cdot (3.0 - 2.0)} = -890$$

Since the initial OFFTCcode was 0 (thus OFFTCsign was irrelevant), the new desired Offset TC code will be 890 and the OFFTCsign bit must be set to "negative".

Example 2:

Assume the same initial conditions as in Example 1 above, except for an initial Offset TC coefficient of +2000. Since a change of -890 is required from the CURRENT Offset TC code:

$$NEWOFFTCcode = +2000 - 890 = +1110$$

Set the Offset TC register to 1110 and set the OFFTCsign to "positive" regardless of how it was set before. Numerical values larger than +/- 4095 indicate the sensor has gross Offset TC errors which the MAX1478 is unable to compensate. The output Offset will be affected by an Offset TC adjustment and the output may even saturate after the new coefficient is loaded. Every Offset TC adjustment MUST be followed by an Offset adjustment to bring the Offset back to the target value.

HIGH PERFORMANCE COMPENSATION

VOLTAGE MEASUREMENT CONSIDERATIONS

The high degree of accuracy to be attained with a MAX1478-based module requires paying particular attention to methods used to measure voltages. Ideally, measurements should be made differentially with respect to a “star” node which includes the Vss of the ASIC. The measurements should be made to within +/- 1mV (0.025% FSO) or better. These measurements should be based on Kelvin sensing techniques. Relative measurements attempting to determine a value by taking the difference between one measurement (reference) and another node should be avoided or performed with caution, because it is possible for the reference point to move in the time its complimentary node is measured. Also, the resolution of the DVM may not provide enough significant digits, etc.

All equipment used in test should be grounded together and should be tied to the same AC leg. The best way to insure this is to connect a single terminal strip to a wall outlet and connect all equipment to it. This equipment should include DVMs, Power Supplies, Oscilloscopes, SwitchBoxes, Computers, Monitors, and ANYTHING connected to the computer that is not optoisolated. Do not assume that all outlets within the same room are connected to the same circuit. In the case of large equipment such as ovens which may require a dedicated circuit, it is advisable to keep the test-system electronics completely isolated from the oven-system ground.

Equipment such as ovens and pressure controllers will contain relays, solenoids, and motors and can generate significant electrical noise. This noise may be difficult to pinpoint, but since it is often periodic, it may be possible to detect if a continuous data acquisition is performed over a long enough time. It is advisable to temporarily suspend the operation of such equipment, if possible, when measurements are being performed.

The MAX1478 compensation procedure does not require measurements of the low-level sensor output; these nodes should be kept undisturbed and as short as possible. With higher system gains, a bypass capacitor across the sensor output node is a must, but may reduce the system bandwidth. If access to these nodes is required, buffer them or measure them with very high input impedance DVMs only, using the shortest of lead lengths (using twisted-pair wires, of course).

Small values such as the low-level sensor output are very susceptible to thermocouple effect since temperature is a key element of sensor test and calibration. Some metals used in the electronics industry have coefficients in the order of 10s of µV per °C. A poorly designed test system can add several millivolts of error to a measurement. Connectors and relays are key culprits. It is essential to minimize the number of interconnections in a test system, particularly inside the oven itself, or anywhere there may be a large temperature gradient. Reducing the number of interconnects and relays also improves the test system reliability.

A single measurement (one sample) is not the preferred way of implementing the measurement procedure. Using filters and built-in averaging algorithms, as provided by many modern DVMs, is also not the preferred method of making a quality measurement, since these methods often mask underlying errors and problems. Much more information can be acquired by manipulating a sampling of several unfiltered measurements. We could look at the standard distribution and min-max to get a measure of the quality (AC component and stability) of a signal.

Often, a parameter to be measured may require some settling time before it is sufficiently stable for a quality measurement. An example of this might be after a change is made to a coefficient, after power-up, etc. The traditional method for addressing these of problems is to employ fixed measurement delays before a measurement is performed. The problem with this approach is that it is non-adaptive to unforeseen systems or procedural changes. It may be very difficult to troubleshoot compensation problems which, for example, may be due to measuring Vout before it has stabilized. For reasons such as this, it is recommended that measurements be performed in a more intelligent and robust fashion. One solution might be to implement each measurement as a series of closed loops where a measurement is only considered valid if two consecutive readings agree within a predetermined amount. A loop counter could be added so that if the conditions are not met after a certain number of readings, the parameter being measured is considered of poor quality and an error is flagged. This approach is adaptive and much more forgiving to changes in test-system variables.

PRESSURE HYSTERESIS

This error can be measured by repeatedly measuring the FSO (sensitivity) of the module at a particular temperature. This is done by subjecting the sensor to several full-pressure excursions. The error will be the difference between the lowest and highest readings and can be expressed as a percentage of FSO. This error becomes more noticeable at colder temperatures, particularly if the sensor DIE contains oils or gels to provide media isolation, partly because their viscosity decreases or, in extreme cases, the medium may solidify. Table 8-1 below is an (exaggerated) example of how this error might affect our calibration. The mean of the 7 readings for sensitivity is 1526µV/V/PSI; ideally the FSO should be compensated on the basis of this value, to obtain optimal accuracy. If the first reading was used, however, the FSO calibration would have been almost 1% in error from the mean.

Measurement #	Reading
1	1540 µV/V/PSI
2	1533 µV/V/PSI
3	1520 µV/V/PSI
4	1518 µV/V/PSI
5	1531 µV/V/PSI
6	1522 µV/V/PSI
7	1517 µV/V/PSI

Table 8-1

Effect of Hysteresis errors on Measurements

TEMPERATURE HYSTERESIS

This error is virtually identical in form to pressure hysteresis, except it occurs with respect to changes in temperature. The other major difference is that it is much more time-consuming to measure since it requires temperature excursions rather than pressure excursions. Where it may have taken a few minutes to perform a pressure hysteresis test, it could take most of a day to perform a similar temperature hysteresis test. One of the more evident ways in which the effect of this error mode can be noticed is during calibration and final device characterization. Given the same temperature point T, slightly different values may be measured for the module output depending on whether the chamber had to be heated to get to the target temperature T, as opposed to having to cool it to get to T.

NON-REPEATABILITY

In general, these errors are defined as those for which a precise explanation or equation cannot be derived to accurately predict the output at any given moment. This includes errors due to pressure and temperature hysteresis, aging effects, time-related drift, cosmic rays, solar flares, presidential election years, etc. These errors are usually the limiting factor in the calibration accuracy of an MAX1478-based product.

THERMAL DEADBAND

Some sensors exhibit a behavior where the voltage Vb will require seconds to minutes to settle after a large change in the excitation current Ib. This is very evident on power-up but may also be noticeable at lower operating temperatures. Since the sensor is dissipating some energy, a finite amount of time is required for the sensor DIE to reach thermal equilibrium with its surrounding. This behavior is very noticeable on some sensors and virtually nonexistent on others. In a MAX1478-based module, it most often shows itself as a drift in the value of Vb after a change is made to the excitation current or after initial power-up. The magnitude of this change may be as much as 10mV over a period of a minute or so; however, the value of Vb will eventually reach a finite value.

MISMATCHED WHEATSTONE BRIDGE

Some sensors are not well balanced, so that at any given temperature as pressure is applied, Vb will change (if under constant current excitation). This implies that the sensor impedance is changing. This bridge imbalance is sometimes intentionally built into a sensor to improve FSO linearity performance. It is usually only a fraction of a percent of FSO; however, with larger amounts there may be a negative effect on the calibration accuracy, because the MAX1478 will interpret any change in Vb as a change in temperature. It is important to mention that the sensor excitation voltage Vb is an essential parameter in calibration and the measurements of it must be accurate. For this reason, we should always measure Vb at the same pressure, unless we know that it is not a function of pressure to any degree that would affect our compensation.

Example:

We are compensating a ratiometric device where the output FSO is 4 volts; thus, a 4mV error will be equal to 0.1% of FSO. A typical bridge excitation voltage might be in the vicinity of 2 volts and 0.1% of this voltage will be 2mV. Since we know that the FSO is proportional to the excitation voltage, we can see that a 2mV error in the measurement of Vb will result in a 4mV (0.1%) error in the output FSO. It is possible (even with a good sensor) for the input impedance of a silicon PRT to change ever so slightly with changing pressure to cause a 2mV error in the measurement of Vb.

FSO LINEARITY

As we mentioned previously, silicon PRTs are inherently very linear devices. For the sake of those who work with ultra-linear metal strain gauge transducers (who are now frowning), we must explain ourselves. Silicon PRTs are sufficiently linear to the extent that the sensor linearity errors are not the limiting source on accuracy. In other words, repeatability errors are usually larger than linearity errors over a wide operating temperature range. For this reason, the measurement of the FSO linearity errors of PRTs can be subject to moderate errors if one is not careful. We are attempting to pull out a minute parameter out of a big bucket of noise. The accuracy of our pressure linearity measurement is only as accurate as our measurement of our FSO, which is only as accurate as our measurement of Offset and FS. For these reasons, it is preferred that we employ a similar approach as with measurements of hysteresis; that is, measure it several times and take a mean value.

TEMPERATURE SOAK TIME

Knowing the temperature of the sensor element itself, as well as knowing if the value is stable has always been important in compensation. However, as our desired accuracy increases, knowing if the temperature is stable becomes much more important. We do not care very much about the absolute value of the temperature, because our compensation procedure does not require the numerical value for temperature to compensate whatever sensor errors exist at a fixed temperature. Obviously, if we compensated the module at one temperature and the temperature subsequently drifted, we would have an error since we would be applying correction coefficients derived for another temperature point.

This problem has traditionally been solved by simply adding a fixed amount of temperature soak time to the test procedure. At times it may not be enough, resulting in calibration errors and yield loss, and at times it may be wasteful of resources (mainly time and money). The MAX1478 provides a unique way of solving this problem precisely and determining the optimal time, every time. Since we know that Vb is very sensitive to T (in the order of several mV/°C), the test system can simply monitor Vb and wait until it reaches a steady-state value. Since the sensor diaphragm is nested deep within the mass of the transducer module, once this key element reaches steady-state temperature, it is very safe to assume that everything else in the environmental chamber has reached that temperature, too. This, in effect, is a closed-loop method that will precisely adapt itself to any kind of process variation such as varying thermal masses of different transducer products or varying quantities of them, ovens with differing thermal capacities, etc.

HIGH-IMPEDANCE NODES

The MAX1478 includes several high-impedance nodes which must be treated with special care. These nodes are listed in Table 8-2 below. Although other pins also have high output impedances, the ones in the table are those requiring the most care during board layout, and are also the most susceptible to noise and to small leakage currents as a result of contaminants on the board which can be aggravated by condensation of moisture during test in an environmental chamber. Errors observable might be temporary, as in the case of crossing the 0°C temperature region from “below”, since any moisture that was previously frozen ice is now free to move and migrate until the conditions are right for the moisture to completely evaporate. During circuit layout, it is very important to minimize the length of these nodes.

It is strongly recommended that any circuit which might be exposed to conditions where moisture could condense be conformal coated. A light coating of SilGel® is recommended, particularly in the areas just mentioned.

NAME	PIN #	DESCRIPTION
INP	14	Signal path non-inverting input.
INM	15	Signal path inverting input.

Table 8-2

High Impedance MAX1478 Nodes

VERIFYING PERFORMANCE AND ACCURACY

Introduction

The MAX1478 Evaluation Kit was compensated at Maxim Integrated Products, Inc. to a total error band of typically ±1% FSO of the sensor's repeatability, or ±40mV (at FSO = 4V). Verification of the pressure sensor error at such an accuracy level requires special attention to the accuracy of test equipment, as well as to the test-system configuration and test procedure, as discussed below.

Verifying the temperature compensation error will not require critical absolute calibration accuracy. In such a case, the requirement for the absolute accuracy can be replaced with a requirement for measurement accuracy and stability over the time of testing only. The tight compensated temperature error band may not be necessarily centered around the zero error, but it will nevertheless exhibit a very low deviation.

Test Equipment Accuracy

The US National Institute for Standards and Technology (NIST) recommends that the combined error of the test equipment should be no larger than 20% of the accuracy of the device under test. Thus, the combined test equipment accuracy should be five times better than the accuracy of the device under test. For example, to verify a 1% evaluation kit accuracy, the combined error of the test system should not be greater than 0.2%. The measurement accuracy of the pressure sensor is a superposition of the several factors (Table 8-3).

Parameter	***Description***	***Recommended Accuracy (% of reading)***
Δ1	Measurement accuracy of the supply voltage at the terminals of the board.	0.04%
Δ2	Measurement accuracy of the output voltage at the terminals of the board.	0.04%
Δ3	Measurement accuracy of the reference pressure.	0.00%
Δ4	Measurement accuracy of the input pressure	0.19%

Table 8-3

Measurement Accuracy Requirements

The maximum worst-case measurement accuracy is a sum of all these components. Thus, each of the error components should be four times lower level than the recommended 0.2%, at 0.05% level. In practical applications, it seldom occurs that all the error components simultaneously reach the maximum in the same direction, so the expected error will be less. The errors can be calculated as:

$$\Delta max = \Delta 1 + \Delta 2 + \Delta 3 + \Delta 4$$

$$\Delta = \sqrt{\Delta 1^2 + \Delta 2^2 + \Delta 3^2 + \Delta 4^2}$$

Voltage Errors

There are four voltage measurements taken during verification test:

- Supply voltage
- Zero pressure output
- Mid-scale pressure
- Full-scale pressure output

Zero is defined by two voltage measurements and FSO is defined by three voltage measurements. Assuming all the voltage measurement errors to be the same, each of them has to be 1/3 of the allowed final error or 0.67%. Since the voltage measurement accuracy can easily be higher than the pressure measurement accuracy, it is recommended that both voltage measurements be made with at least a 5_ digit DVM offering 0.0001V resolution on a 5V range and accuracy not worse than 0.0002V (∆1 and ∆2 = 0.004% of 5V). This would allow a combined pressure error of 0.19%.

It should be pointed out that, if a significant current is drawn, voltage drops due to the interconnecting wires resistance may affect voltage measurement accuracy; e.g., if a 10Ω connecting wire's resistance is inserted, the supply current of 3mA will create a significant 30mV error, equivalent to 0.6% of supply voltage. It is therefore recommended that all the voltage measurements be based on 4-wire Kelvin measurements.

Reference Pressure Errors

The evaluation kit includes a **gauge** pressure sensor. The reference pressure port on the sensor is in the form of a small vent hole in the bottom of the sensor package (between the pins). The sensor output is proportional to the difference between the input pressure and the reference pressure.

Low reference pressure error ∆3, while it is easiest to achieve, it is the most neglected component, often significantly affecting the accuracy of measurements. For proper measurements, the sensor housing should be inserted into an enclosure (box). This enclosure should be connected via a pressure tube to the reference port of the pressure calibrator or (if such a port is not available) connected very close to the sensor calibrator. Failure to implement such configuration creates the following problems:

- The pressure inside the temperature test chamber (where the sensor usually is located during test) fluctuates as a result of the fan found in many ovens. This fan often has its speed variable with temperature and time. Furthermore, pressure generated by the fan usually is vented through the uncontrolled parasitic vent holes in the oven housing, with a pneumatic resistance which can change with temperature and time. The oven's fan can create pressures within 0.5 to 5kPa (0.5 to 5% of 100kPa, which is the approximate range of the demo sensor).

- Many ovens use liquid nitrogen or carbon dioxide for cooling. Injection of the cold gases under high pressure into the oven creates large pressure spikes which can significantly "degrade" the performance of the sensor.

- The difference in pressure between the sensor reference port and the pressure calibrator reference port is further degraded by a variable pressure in the room, resulting from such factors as air-conditioning cycles, opening of doors, air movement resulting from people movement, etc.

- Equalizing reference pressures for a test sensor and pressure calibrator should reduce this error to zero, allowing for 0.019% error of the input pressure.

Input Pressure Error

This error is directly affected by the calibration accuracy of the pressure tester and the pressure leaks in the test system. Required accuracy of the pressure test equipment in this example is 0.19%, as derived previously.

Pressure leaks are a major source of errors, as small leaks are difficult to detect. While most users check for pressure leaks during the interconnection of the sensor at 25°C, quite often the leaks are created when the temperature changes due to temperature expansion of materials used. Pressure leaks result in the FSO being smaller than expected, and often also affect the measured pressure nonlinearity.

Sensor Drift

The MAX1478 cannot compensate sensor instability nor pressure or temperature hysteresis. Super-stable sensors are quite expensive. The MAX1478 Evaluation Kit is shipped with a generic sensor, which is reasonably stable. It performs the job quite well, but under certain conditions it may drift with time, shifting the calibration. If such a case is suspected, it is recommended that the raw sensor data be monitored. Reference sensor data measured during factory calibration is included with the Kit. By comparing both sets of data, original and newly measured, the diagnostic process could be accelerated.

Moisture Condensation

Condensation of moisture on the electronics may create shorting bridges and leakage current. One of the options for elimination of this problem is purging the sensor subassembly with nitrogen during the entire test, provided it is connected in such a way that reference pressure is not affected. Another option is to coat the entire subassembly (except for pressure ports and test connectors) with a conformal coating.

MAX1478 CIRCUIT DESIGN

The MAX1478 contains two fundamental types of coefficients. The first type are the “hard-coded” coefficients that are set to a specific value for the entire module product line. These are primarily external resistors (for example, Rftc), but they may also include the value of certain internal registers as well. In either case, the values selected for these coefficients should provide enough dynamic range to accommodate all sensor error distributions for the particular sensor parameter in the product line. The other type of coefficients must be set to a value that is unique to the specific Sensor/ASIC pair that is being trimmed; for example, “Offset”. These are all electronically programmed values; hence the term “Electronic Trim”.

THE COEFFICIENTS

Table 9-1 lists all of the MAX1478 coefficients. They are listed in the order in which they would normally be initially programmed.

COEFFICIENT	*DESCRIPTION*
Risrc	External resistor. Determines the baseline bridge drive current.
Rftc	External resistor. Determines the maximum allowable FSO TC feedback.
IRO DAC	3-bit front-end coarse offset adjustment DAC.
IRO SIGN	Sign bit determines whether to add or subtract IRO DAC value.
PGA	Programmable 3-bit register. Sets the signal path gain.
FSODAC	(12 bits). Sets the baseline bridge excitation current (determines FSO).
OFFSET Sign	Programmable register. Changes the polarity of the Offset correction voltage.
OFFSETDAC	(12 bits). Used to set the Offset (zero pressure output).
FSOTCDAC	(12 bits). Dynamic DAC sets the FSO TC correction.
OFFTC Sign	Programmable register. Changes the polarity of the Offset TC correction voltage.
OTCDAC	(12 bits). Dynamic DAC sets the Offset TC correction.

Table 9-1

The MAX1478 Coefficients

Table 9-2 lists test data from a typical generic silicon PRT. This data will help us throughout the rest of this chapter and will be referenced by examples, compensation procedures, etc. This data may vary considerably from certain types of sensors, such as metal film, ceramic, etc., for which the MAX1478 is not optimized. Additional external circuitry may be required to accommodate these types of sensors.

PARAMETER	SENSOR DESCRIPTION	TYPICAL VALUES
Rb(T)	Input/Output Impedance	5kΩ at +25°C
TCR	Input/Output Impedance Tempco	2600 ppm/°C
S(t)	Sensitivity	1.5mV/V/PSI @ +25°C
TCS	Sensitivity Tempco	-2100 ppm/°C
O(t)	Offset	12 mV/V at +25°C
OTC	Offset Tempco	-17% FSO
S(p)	Sensitivity Linearity Error as % FSO, BSLF (Best Straight-Line Fit)	0.1% FSO BSLF
P_{MIN}	Minimum Input Pressure	0 PSI
P_{MAX}	Maximum Input Pressure	10 PSI

Table 9-2

Sensor Information for Typical Silicon PRT

Risrc

This coefficient is an internal/external resistor that sets the maximum bridge current (in conjunction with FSODAC). In the majority of cases, the sensor bridge impedance will be about 5kΩ, and at room temperature, it will be operated with about 500µA of excitation. This will yield a Vb of about 2.5 volts. Therefore, dividing 500µA by the current-mirror ratio (AA~14), one can determine the nominal current that must flow through Risrc to be about 36µA. The valid voltage range at ISRC is from V_{SS} +1.3V to V_{DD}-1.3V. We chose an operating voltage of 2.5 volts, therefore the ideal resistor value for Risrc would be around 69kΩ, which is to be rounded to a nice number like 51kΩ because the 12-bit FSODAC offers considerable dynamic range. Risrc is not really an independent variable, since the ratio of Rftc to Risrc is relevant. Equation 9-1 can be used to approximate the value for Risrc.

$$Risrc \cong AA \cdot Rb(T) = 14 \cdot 5k\Omega$$

Equation 9-1

Rftc

This resistor determines the maximum allowable amount of temperature correction (feedback) allowed (when the value in FSOTCDAC is a maximum) on the current source. Since the PRT will always have a positive temperature coefficient, usually greater than the TC of the sensor's sensitivity, it will always be necessary to "rotate" this TC curve in a clockwise direction (Figure 7-2). With Rftc in place, the current source can be modulated (by Rftc and FSO DAC) over temperature. For any given temperature, only one unique voltage *Vb* will give the ideal desired output FSO. The value of this resistor also depends on the value of Risrc. For further analysis of the interaction of Rftc, refer to Equation 5-21 derived for Vb. The large dynamic range of the 12-bit FSOTCDAC allows considerable freedom in the selection of the value for Rftc. The internal value for Rftc is suitable for most applications and should be used.

A value of 50-100kΩ for the external Rftc works well for normal PRTs. In cases of unusual PRTs with TCRs of less that 1000ppm/°C, it may be necessary to reduce this value. Values of Rftc that are too high (i.e., 200KΩ) will probably not provide enough feedback. In such cases, full-scale values in FSOTCDAC will still not rotate the TC curve enough in a clockwise direction. The compensated module would show a positive TC for FSO. Values for Rftc that are too low will not optimize the dynamic range of the DAC coefficients properly. Choose a value such that the mean value (of a batch of transducer modules) for the FSOTC DAC coefficient is about 1/2 scale (0800h). One can use Equation 9-2 to approximate the value of Rftc for most silicon PRTs.

$$Rftc \cong \frac{Risrc \cdot 500\,ppm/{}^{o}C}{TCR - \left|TCS\right|} = \frac{51k\Omega \cdot 500ppm/{}^{o}C}{2600\,ppm/{}^{o}C - \left|-2100ppm/{}^{o}C\right|} = 51k\Omega$$

Equation 9-2

FSOTC feedback is determined by both Rftc, and the FSOTCDAC. The value selected for Rftc must also insure that FSOTCOUT is operated within its allowed common mode range which will depend on the sensor excitation voltage swing over temperature.

PGA

The signal path has a 3-bit programmable gain amplifier (PGA) with gains from 41 to 230, in steps of 27. The PGA register can be thought of as a “hard-coded” register, since it is often possible to find a gain setting that works for an entire family of sensors.

The PGA is also referred to as the coarse gain register. Since there is a 12-bit DAC to program the sensor excitation and since the sensor’s FSO is proportional to the excitation voltage, one can refer to the FSO DAC as the fine gain or FSO register. The PGA gain setting is one of the first parameters to be set. It is usually done at room temperature. The ideal PGA gain can be determined by Equation 9-3, where the nearest available PGA gain setting is chosen. If the desired gain is greater than 230 (sensor FSO too low), it may be possible to operate the sensor at a slightly higher Vb. If the desired gain is below 41 (sensor FSO too high), it may be possible to operate at a slightly lower Vb or the sensor output may be attenuated with a resistor.

Example:

$$PGA = \frac{desiredFSO}{SensorFSO} = \frac{desiredFSO}{S(T) \cdot Vb \cdot \Delta P} = \frac{4V}{0.0015 \cdot 2.5 \cdot (10-0)} \cong 107$$

Equation 9-3

FSODAC

The value of FSODAC establishes the baseline current through the sensor and determines the sensor’s low-level FSO and Offset output. This parameter is usually set in conjunction with the PGA setting, the goal being to find a value for the PGA so a voltage Vb near Vdd/2 produces the ideal room-temperature FSO. Normally, this is done with the FSOTCDAC initially set to mid-scale. Once this coefficient is set, any subsequent adjustments to Vb (to correct for temperature errors) will be made by the value in FSOTCDAC being used to modulate Vb. Vb should not be operated below V_{SS} +1.3 volts or above V_{DD}-1.3 volts.

The absolute value of Vb is important from several standpoints. Vb should normally be set as high as possible to minimize the required system gain and improve the signal-to-noise ratio. Vb changes with temperature. Depending on the sensor’s TC and the magnitude of this voltage, Vb may change as much as 1 volt over temperature. Thus, when setting the value of Vb at room temperature, it is important to provide enough headroom. With this in mind, at room temperature, Vb should not be less than V_{SS}+2 V or larger than V_{DD}-2 V. It is also possible that if the sensor has a very large Offset, the signal path may saturate. If this is the case, it is necessary to first reduce Vb to a low value and make a coarse Offset adjustment.

OFFSET DAC and OFFSET Sign

Once the room-temperature FSO is set, one can adjust the OFFSET DAC and the OFFSET Sign bit to set the output voltage to the desired value. This should be performed with the OFFTC DAC set to "0". Both the OFFSET DAC and the OFFTC DAC outputs are gained up at the summing junction by a factor of about 2.3, so an output of 4 volts from one of these DACs is increased to the internal equivalent of +/- 9.2 volts into the signal path, depending on the sign bit. This is true, even if V_{DD} is only 5 volts. The output of the MAX1478 is, of course, limited by Vss and Vdd.

FSOTCDAC

This DAC takes a portion of BDRIVE as its reference. The output of this buffer FSOTCOUT is used to drive Rftc. Thus, the coefficient determines the amount of Vb feedback control applied to the current mirror reference node ISRC. If we were to plot the value of Vb of a sensor under constant current excitation, we would simply get a graph of TCR. Its slope for a PRT will be several thousand ppm/°C. One of the constraints of the MAX1478 architecture is that TCR (bridge TC) must be larger than the magnitude of TCS (FSO TC). For voltage mode sensors, where TCR is lower than TCS, an external temperature reference must be provided (which can be easily implemented with a diode). This is due to the fact that TCS errors are trimmed by reducing Vb at hotter temperatures. In effect, the TC graph is "rotated" clockwise by increasing the feedback (either by reducing the value of Rftc or increasing the FSOTC coefficient).

OFFTC DAC and OFFTC Sign

Since Vb changes with temperature, a signed portion of this voltage can be taken into the summing junction and used to correct for output Offset TC errors. A gain of 2.3 is realized at the summing junction. At any unique temperature, it is necessary that the FSO TC be adjusted first, before the Offset TC is adjusted, because the FSO TC adjustment influences Vb, which becomes a reference to the Offset TC DAC.

IRO DAC

Input Referred Offset correction (coarse offset correction) is optional. Normally, it is not required that the sensor offset be nulled prior to amplification by the PGA. Applications requiring the higher PGA gain settings may, however, necessitate a coarse offset correction if the sensor has high offset errors. This will prevent the PGA from saturating and also helps to "center" the trimming range of the (fine) Offset DAC. IRO corrections are performed by simply measuring the sensor offset error at room temperature with the ideal BDRIVE voltage and selecting the appropriate IRO DAC code and IRO Sign bit from the tables in the data sheet. An alternative method that does not require disturbing the differential output of the sensor involves using the PGA. If the sensor has no offset error, then changes in the PGA gain will not cause the output of the PGA to change. We can therefore use a successive approximation method to select an IRO value that minimizes the change in the output of the PGA as we change the PGA gain from minimum to maximum.

DESIGNING THE MODULE

To review, we have defined our objective as follows: to produce a ratiometric pressure-sensing module using a normally behaving PRT and a MAX1478 operating with a supply of 5 volts with a total accuracy within +/- 1% of the sensor's repeatability errors. The heart of the calibration and module performance will be based on the values of the temperature coefficients. More than 95% of the test time will be consumed in determining these coefficients because temperature measurements are involved and, as we noted, it may take as much as 1/2 hour per temperature point.

When considering the design of a sensing module, one of the most important items to consider is the total accuracy required. Although other important issues also exist (i.e., cost, reliability, manufacturability, etc.), we will not address them here. It should be overwhelmingly clear that the total combined effects of the "Misc." errors defined previously should be a small fraction of the total error budget. After compensation, the only remaining errors should be the following:

- Calibration
- Compensation
- Miscellaneous

Calibration errors refer to inaccuracies in our transfer standards or methods, which produce a degree of disagreement between our module and the desired physical parameters which we are attempting to measure. Calibration errors are defined over a very limited set of conditions (i.e., temperature, humidity, etc.).

Compensation errors in our case will refer primarily to errors of temperature (FSOTC and OFFTC), which the MAX1478 is expected to correct. Since we can only control the first two error sources above, it becomes clear that the lower the "Misc." errors are, the more likely we will be of meeting our total error budget.

Although the MAX1478 will not introduce significant errors to our module, it cannot be completely ignored. Fortunately, the few existing MAX1478 errors are highly predictable and, unlike with most sensors, these errors are extremely consistent from part to part. Also, these errors can easily be extrapolated during test, if need be. This is usually not necessary, however. The most practical method for compensating a MAX1478 transducer module is to treat it as a black box which has an Offset TC error, FSO TC error, etc. The DACs in the MAX1478 can then be used to correct these errors without regard to their true source.

If we were producing a sensor-only product, that is, a module that did not contain signal conditioning, our definition of a good sensor (with respect to performance only) might be the following: low TC errors, good linearity, low "Misc." errors, and FSO and Offset properly calibrated. Although this is generally desirable, using the MAX1478 implies that one or more of these parameters are pushing us outside our total error budget and we expect the MAX1478 to correct this. Once the MAX1478 is factored into the equation, these errors are no longer a problem so long as they are within the trimmable range of the MAX1478. Whether the Offset is 1mV or 50mV is of no consequence, since they can both be trimmed out in the same way and in the same amount of time. However, when we look at a wider picture and bring the test system into view, our definition of a good sensor changes somewhat.

The design engineer will strive to minimize test time, in order to reduce cost. Also, the test algorithm should involve as little temperature testing as possible, since this is undeniably the single most time-consuming aspect of test. In the MAX1478, as in any signal conditioning ASIC, a trade-off always has to be made between the dynamic range and the quantization error of any error coefficient that is to be trimmed. That is to say, for any fixed, tolerable quantization error, the dynamic range needed to compensate a given sensor error is directly proportional to the distribution of errors.

Example:

If 256 codes are needed to compensate a sensor Offset distribution of 10mV, twice as many would be needed if the distribution was 20mV; this assumes the same quantization error in both cases.

The MAX1478 contains 12-bit DACs for use as trim coefficients. However, there are limitations on the dynamic range of these coefficients. Close sensor parameters yield great savings in manufacturability, as well as test. In such a case, global trimming methods can be used to great advantage.

As a result, our new definition of a good sensor is as follows: low “Misc.” errors, all other errors within trimming range of the MAX1478, and close distribution of sensor parameters from lot to lot. As can be seen, this definition is not as much driven by the MAX1478 as it is by the test system and issues of practicality, test cost, yield loss, manufacturabilily, etc. If the sensor errors are closely distributed, *considerable* reductions in test time can be achieved. One should confirm that the sensor’s non-repeatability errors plus the Electronics & Test systems errors are measurably less than our target accuracy. For example, if the sensor shows repeatability errors of 0.2% and Electronics & Test system errors are 1%, then we probably would have a difficult time making *production* parts that would average better than 1.5%, out the door!

Component Values

It is strongly recommended that the ratiometric schematic provided at the beginning of this paper be used as a starting point. If using a conventional silicon PRT, it will be very unlikely that any component values will need to be changed and the internal resistor values should be selected. It is very likely that some additional components will be needed, for things such as ESD protection of the sensor or MAX1478, module miswiring protection, etc. If the recommended internal component values are used, the following parameters will be set as shown:

R_{ISRC} = 75kΩ Maximum bridge current will be 0.6 mA.
Rftc = 75kΩ Suitable STC range for most PRTs.

THE COMPENSATION PROCEDURE

Below, we will offer a compensation procedure. This procedure is specifically designed for use with silicon PRTs used to sense pressure. It must be stressed that there is no universal procedure. Every application will demand a specific way of performing compensation so as to minimize test time by taking advantage of the specific strengths of the particular module and test equipment being used. This procedure is derived from Maxim's own experience in compensating MAX1478 evaluation kits. These evaluation kits contain a generic low-pressure sensor housed in a small metal case. The two test temperatures TC and TH are -40°C and +125°C, respectively, but the procedure can be applied to any two arbitrary test temperatures where TC<TH. We will be compensating a ratiometric device with a supply voltage of 5 volts and a compensated output voltage range of 0.5 through 4.5 volts. It is assumed that the user has read all the preceding compensation material in this chapter and that he/she is therefore familiar with the equations, procedures, and symbols used.

We begin with some definitions.

TC	Temperature reference 1 (Cold Temp)
TH	Temperature reference 2 (Hot Temp)
Pmin	Minimum operating pressure
Pmid	Mid-scale operating pressure
Pmax	Maximum operating pressure
Vdd	Supply voltage
Vout	Module output voltage
Vb	Sensor excitation voltage
VbC	Ideal sensor excitation voltage at TC
VbH	Ideal sensor excitation voltage at TH
IRO	Input Referred Offset coefficient
α	FSO coefficient
β	FSO TC coefficient
δ	Offset TC coefficient
γ	Offset coefficient

COEFFICIENT INITIALIZATION

Step 01 Loading the default coefficients.

Calibration and temperature compensation is performed by writing to the MAX1478 registers (not the EEPROM). This can be performed at any temperature and pressure. Set Vdd to 5 volts. Kelvin sensing is strongly recommended. Optionally, confirm that the current consumption is as expected. In the absence of specific sensor distribution data, the following coefficients are recommended to be loaded into the registers to start:

OFFTC	Offset TC coefficient. Set it to 0.
FSOTC	FSO TC coefficient, β. Set it to 0x800.
OFFSET	Offset; set it to 0.
FSO	FSO, (current source) set it to 1/4 scale, 0x400.
PGA	Signal path gain. Set it to minimum, A = 41.
OFFSET Sign	Set it to "1" (positive).
OFFTC Sign	Set it to "1" (positive).
IRS	If using internal resistors, set the IRS bit to "1".
IRO	If the sensor has low initial offset, set it to +0; otherwise select an appropriate value.

Throughout our test, it is imperative that the supply voltage be checked periodically and actively maintained at exactly 5.000 volts! The alternative would be to measure Vdd and ratio all pertinent readings accordingly, but this is not the preferred method.

Step 02 Initial Vb and Offset adjustment.

Set the temperature to TC and pressure to Pmin. Using the FSO register, adjust Vb to 1 Volt. Using the Offset register, and optionally the OFFSET Sign bit, set $Vout$ to 500 mV.

Step 03 Compute and set the optimum signal path gain.

Change the pressure from Pmin to Pmax and determine the current FSO (Vout@Pmax-Vout@Pmin). Leave the pressure at Pmax. Currently our signal path gain should be 41 (minimum). Our sensor excitation voltage is 1 volt; we use this low initial value to minimize the chances of saturating the amplifier. At the moment, our measured FSO should be less than our desired value. Our target Vb at -40 °C should be about 2 volts. The MAX1478 has 8 selectable gains: 41, 68, 95, 122, 149, 176, 203, and 230. Chose a gain such that:

$$currentSpan \cdot 2 \cdot A \cong desiredSpan$$

Equation 10-1

Where:		
	currentSpan	is the value that we measured in the step above
	A	is the signal path gain
	desiredSpan	in our example is 4 volts

Example: We measured a value of 0.5V for currentSpan. We multiply this value by 2 to get 1V. Dividing our desired FSO of 4V by 1V tells us that we require approximately 4 times more gain than we currently have. Since our current gain is 41, our best choice for the new gain will be 176.

Reprogram the PGA with the new gain. Readjust the Offset to read 4.5 volts (we should be at Pmax).

Step 04 Compute and set the optimum VbC, and readjust the Offset.

The pressure should still be at Pmax; change the pressure back to Pmin and compute the current FSO. Measure Vb and calculate the ideal value for VbC as:

$$VbC = currentVb \cdot \frac{desiredSpan}{currentSpan}$$

Equation 10-2

Using the FSO register, set the sensor excitation voltage to VbC. Using the Offset register, set the Offset to 0.5 volts. With sensors that have large negative Offset TCs, this value may not be adequate, as the output stage may saturate once the temperature is raised to TH. In such a case, an initial coarse Offset TC correction may be required.

Step 05 Determine α, and β pairs at TC.

Log the value of VbC, α1C, and β1, which should be 0800h. Change β to 0C00h; call this β2. Adjust α until VbC is restored; this new α will be called α2C. Also, store the signed value of δC (Offset TC coefficient; in our example it should be 0, since we did not perform a coarse OFFTC correction) and γC (signed Offset coefficient).

Step 06 Compute and set the optimum VbH and readjust the Offset.

Raise the temperature to TH and readjust the Offset to read 0.5 volts. Compute the current FSO by applying pressure as before. Measure Vb and calculate the ideal value for VbH as:

$$VbH = currentVb \cdot \frac{desiredSpan}{currentSpan}$$

Equation 10-3

Using the FSO register, set the sensor excitation voltage VbH. Using the Offset register, set the Offset to 0.5 volts.

Step 07 Determine α, and β pairs at TH.

Log the value of VbH, α2H. Change β back to 0800h. Adjust α until VbH is restored; this new α will be called α1H.

Step 08 Compute and set the linear FSO TC coefficient.

Use the previously acquired data along with Equations 10-4 and 10-5 to determine the values of α and β. Program these values into the MAX1478. The FSO TC coefficient β should be programmed into FSO TC DAC. Vb should now be within better than 1% maximum error from VbH. Use the FSO register if needed to trim Vb to the value of VbH exactly.

$$\beta = \frac{\beta 1 * \alpha 2H + \beta 2 * \alpha 1C - \beta 1 * \alpha 2C - \beta 2 * \alpha 1H}{\alpha 2H + \alpha 1C - \alpha 1H - \alpha 2C} \qquad \alpha = \frac{\alpha 2H * \alpha 1C - \alpha 1H * \alpha 2C}{\alpha 2H + \alpha 1C - \alpha 1H - \alpha 2C}$$

Equation 10-4 **Equation 10-5**

Solutions for the FSO TC and FSO Coefficients

Step 09 Compute and set the Offset TC coefficient.

Restore the values δC and γC. Measure Vout at Pmin; call this VoutH. VoutC was forced to be 0.5 volts at TC; therefore, any change at TH is an Offset TC error that must be corrected. Use these two values along with VbC and VbH to calculate the Offset TC coefficient change required using the Offset TC Equation 10-6 derived previously. Our equation generates a value which is the change required from the current Offset TC coefficient. In our example, the Offset TC was set to 0, but it could have been any arbitrary number. Program the Offset TC coefficient. Set the OFFTC sign bit, if required. Using the Offset register, and optionally the OFFSET Sign bit, adjust the Offset to 0.5 volts.

$$OFFTCcode = \frac{4095 \cdot (VoutC - VoutH)}{2.3 \cdot (VbH - VbC)}$$

Equation 10-6

Offset TC Correction

This completes the temperature compensation procedure. Our total error will be in the order of 1%, depending on the sensor type and the temperature range. If we wanted, we could now go back to temperature TC and verify our module performance. We might also wish to make minor changes to the FSO and Offset as required. We may also wish to return the module back to room temperature and make a final FSO and Offset adjustment there instead, to perform a Best Straight Line Fit compensation.

SPECIAL APPLICATION

SENSORS WITH LOW TCRS

As we have previously mentioned, it is a fundamental requirement of the MAX1478 architecture that the sensors TCR be greater in magnitude than TCS. Also, they should be opposite in polarity.

Figure 11-2 shows an example where the sensor TCR is less in magnitude than its TCS. Since the TC slope of TCS is more negative than TCR (Vb) is positive, the resultant effect is that the natural FSO TC (uncompensated FSOTC) will be negative; i.e., the sensor FSO will decrease with increasing temperature. Since the FSO TC feedback circuit can only “rotate” TCR in a clockwise direction (decrease the TC of the current source), we would be unable to compensate this sensor.

One solution to this problem is to add a positive TC to our current source. In such a case, both the current source output current and TCR would increase with temperature, by an amount which is the algebraic sum of the two. Their combined effect would make Vb appear to have a greater TC than TCS. We could then “rotate” it in a clockwise direction using the FSO TC coefficient until the slope of Vb over temperature is exactly opposite the slope of TCS. Our FSO would then be compensated (flat) over temperature.

Figure 11-3 shows the basic MAX1478 current-source implementation, except that a transistor (could also be a diode, thermistor, etc.) and an additional resistor have been added in parallel with Risrc. Since the junction voltage of the transistor will decrease with temperature, the current across Isrc is increased with temperature. This has the effect of adding a positive TC to the current source. The Vbe TC of the transistor is (inherently) fixed at about 2.1mV/°C; therefore the ratio of this constant (Vbe(t)=2.1mV/°C), and its associated resistor, to the voltage across Risrc will determine the modified TC characteristics of our now imperfect current source.

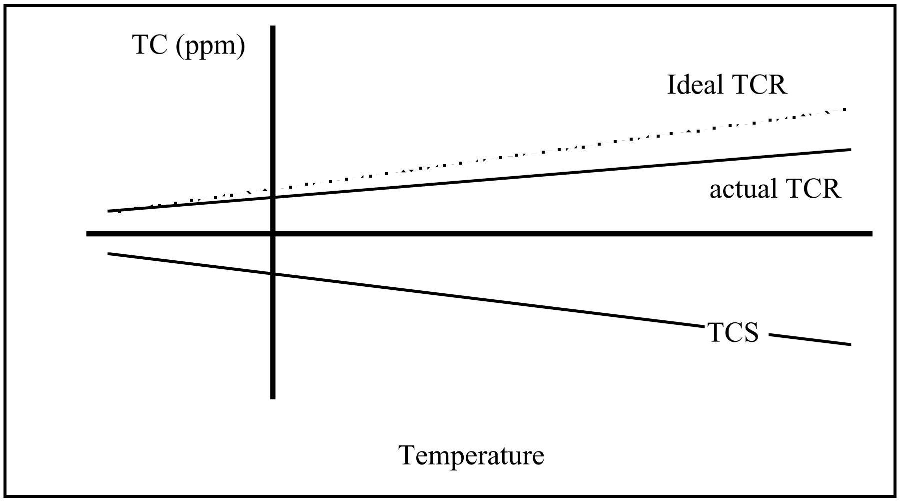


Figure 11-2

Example of a Sensor Whose TCR is Less in Magnitude Than its TCS

Because our temperature reference will now be effectively in two locations (i.e. at the sensor element and also at the transistor), it is advisable to keep the contribution due to the transistor as small as possible. In this way most of the temperature sensing is performed at the sensor element itself, thereby preserving most of our close sensor element temperature tracking. Increasing the value of Risrc reduces the temperature contribution signal due to the transistor. If an external transistor or diode is used, some system equations will require appropriate modifications.

Also note that an additional resistor could be added between pin ISRC and the emitter of Q1 in Figure 11-3. The ratio of Risrc to Rx will determine the modified temperature coefficient of the current source.

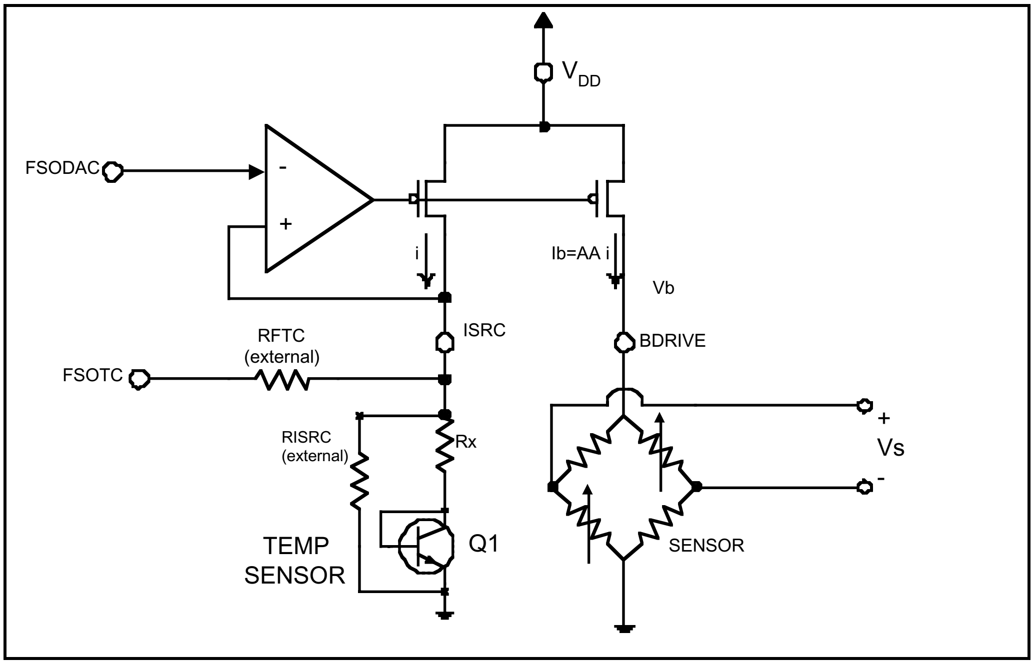


Figure 11-3

A Transistor is Added to the Current Source to Accommodate Low TCR Sensors

THE MAX1478 EVALUATION KIT

EV KIT Quick Start
located on page 2

GENERAL DESCRIPTION

The MAX1478 evaluation kit (EVKIT) demonstrates piezoresistive sensor compensation and calibration using the MAX1478 and a computer. The kit includes an assembled and tested PC board, complete with a factory-calibrated sensor. The software and computer are NOT required for performing the initial performance evaluation, since the EVKIT is already compensated. A ten-pin ribbon cable connects the board to the PC's parallel printer port, allowing the board to be evaluated inside an environmental chamber. The software requires a PC running Windows 95/98.

FEATURES

- Proven PC Board Layout
- Convenient test points provided on board
- Fully Assembled and Tested
- Includes Pressure Sensor
- Factory Calibrated to within 1% of Sensor Repeatability Error over Temperature
- LabView based software

ORDERING INFORMATION

PART	TEMP. RANGE	PIN-PACKAGE
MAX1478EVKIT	-40ºC to +125ºC	20-SOIC

Table 12-1

MAX1478EVKIT PARTS LIST

QTY	PART
1	MAX1478EVBRD assembled, tested, and calibrated circuit board
1	MAX1458KEY Parallel Port Interface Assembly
1	10 pin ribbon cable
1	3 1/2" Software Disk, "MAX1478 Evaluation Kit"

Table 12-2

MAX1478EVBRD PARTS LIST

REFERENCE	QTY	DESCRIPTION
C1-3	3	0.1uF ceramic X7R capacitors
C4	1	leave open
D1	1	6.2V Zener Diode
JP1-4	0	leave open *(shorted on board)*
P1, P3	2	4 pin headers
P2	1	2 x 5 pin header
P4-5	2	8 pin headers
Q1	1	2N3904 NPN small signal transistor (leave open)
R1-20	20	leave open
S1	1	Lucas NovaSensors (Fremont, CA) NPH-8-100GH (TO-8 package, 100kPa gauge)
S2	0	unused, alternate sensor site
U1	1	MAX1478

Table 12-3

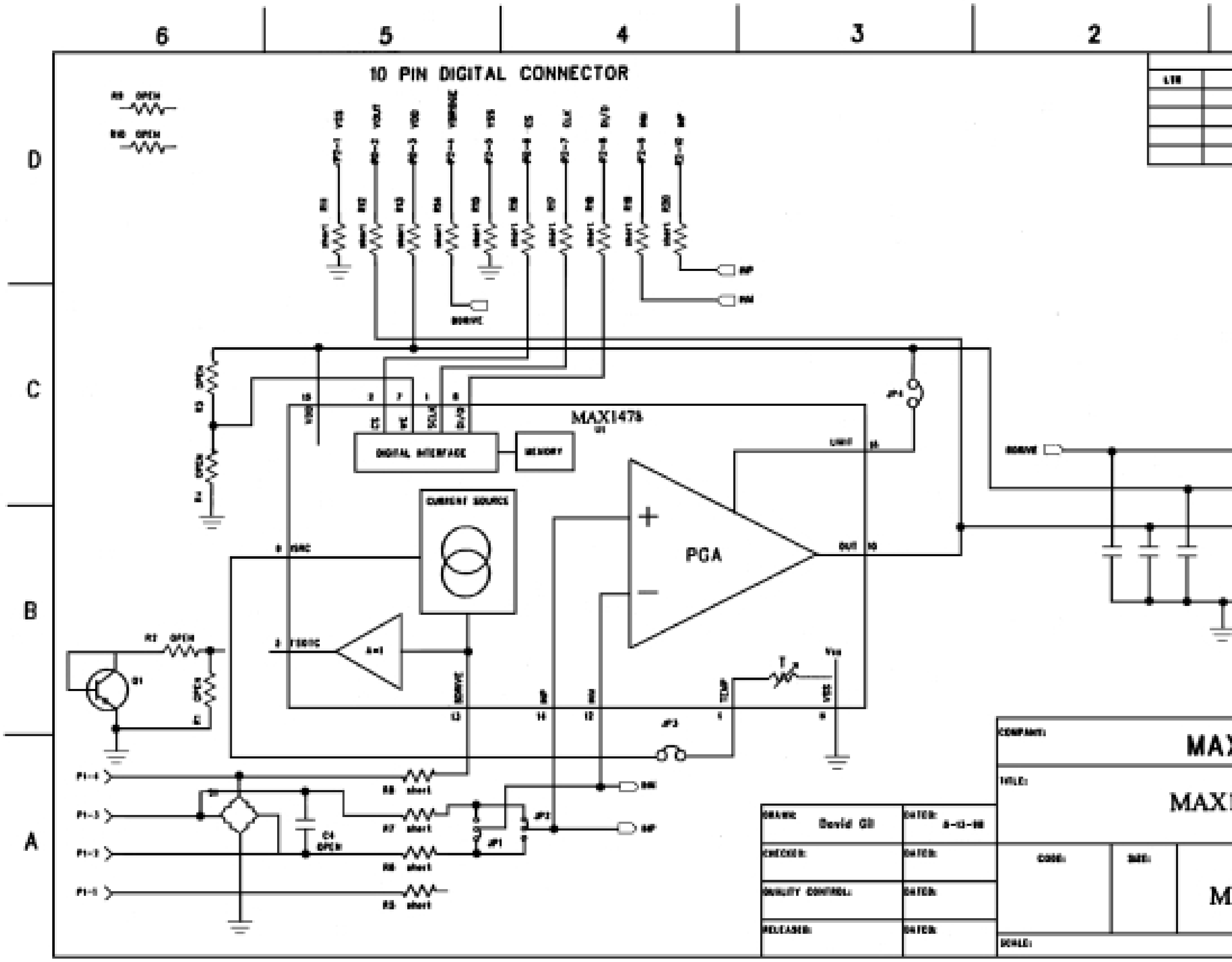
MAX1478EVKIT QUICK START

The quick start procedure can be used to evaluate the initial factory calibration accuracy, and also to allow the user to modify the calibration coefficients. A much more comprehensive test procedure is provided in Chapter 13. Persons not familiar with digital trim ASICs should follow the test procedure outlined in Chapter 13.

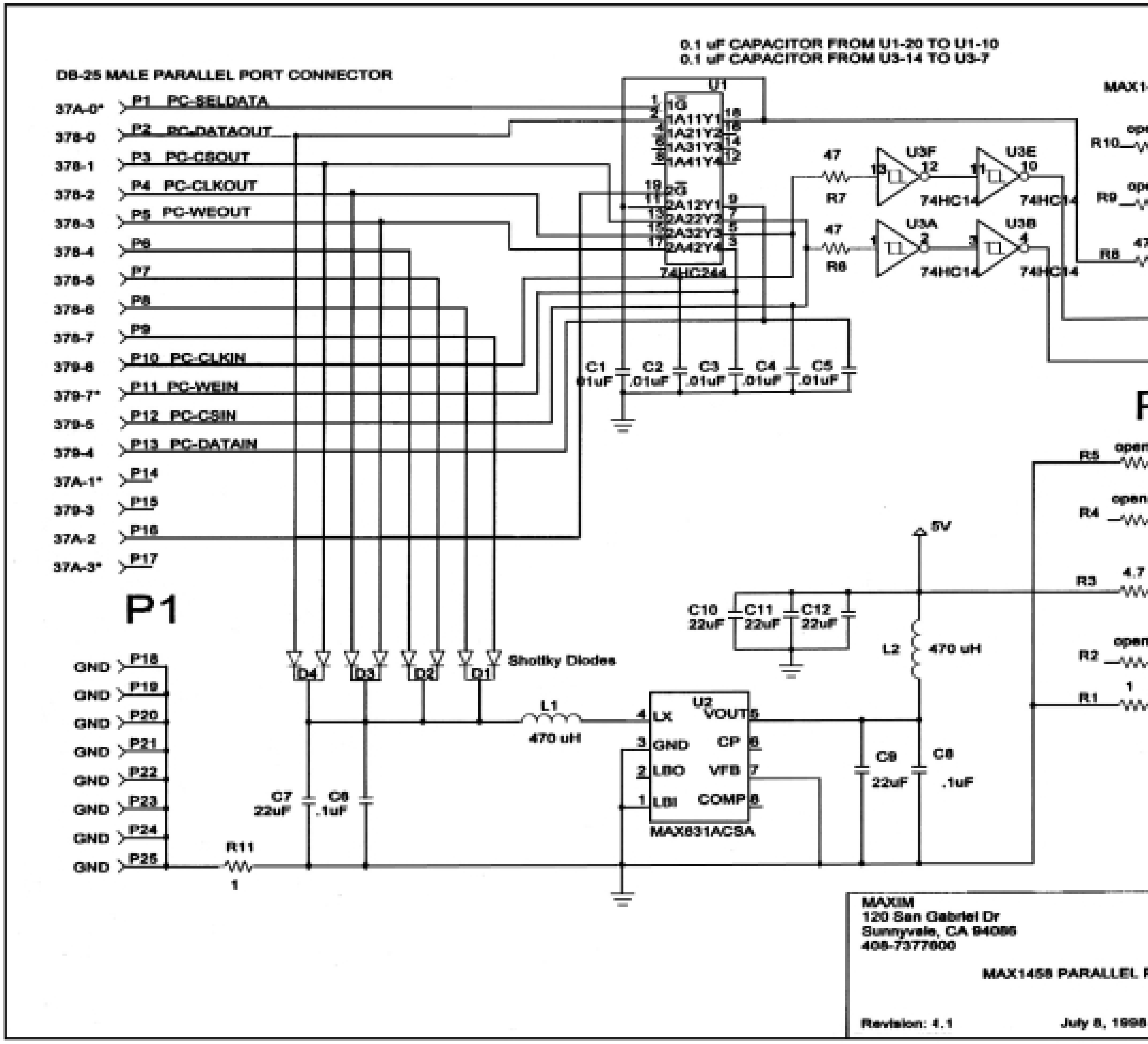
1. Install the software on the PC
2. Connect the MAX1458/MAX1478 key into the PC parallel port
3. Connect the EVKIT board to a 5.000V power supply
4. Connect the sensor port to a pressure controller
5. Connect the EVKIT to a DVM
6. Place EV kit board in an environmental chamber and/or apply pressure stimulus to the sensor. Observe output on DVM.
7. To modify coefficients, connect the EV kit board to the MAX1458KEY
8. Start the software by double clicking on the MAX1478.exe icon
9. Use the software interface to communicate with the MAX1478 and alter coefficients

DETAILED DESCRIPTION OF HARDWARE

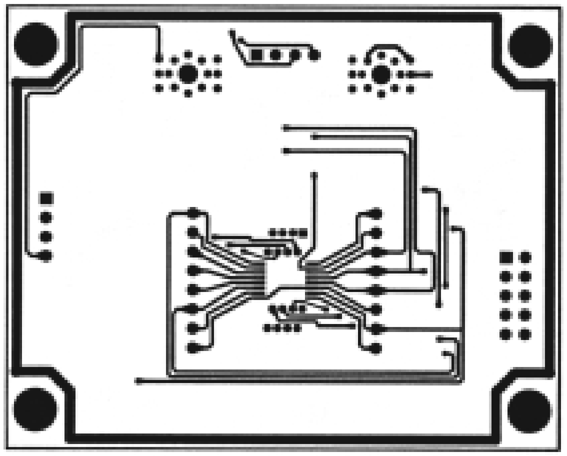
The MAX1478 (U1) performs analog temperature compensation on piezoelectric sensors. As shipped from the factory, a sensor is installed at site S1. The MAX1478 EEPROM contains the temperature compensation coefficients read by the MAX1478.



6
5
4
3
2
D
C
B
A
10 PIN DIGITAL CONNECTOR
R9 OPEN
R10 OPEN
VOUT
CS
CLK
SDRIVE
INP
INM
OPEN
OPEN
MAX1478
U1
DIGITAL INTERFACE
MEMORY
CURRENT SOURCE
PGA
+
−
A=1
ISRC
FSOTC
UNIF
OUT
VDD
VSS
Vss
TEMP
JP1
JP2
JP3
JP4
R7 OPEN
OPEN
Q1
R8 short
R7 short
R6 short
R5 short
C1 OPEN
P1-4
P1-3
P1-2
P1-1
INM
INP
SDRIVE
COMPANY:
MAX
TITLE:
MAX
DRAWN: David Gil
DATED:
CHECKED:
DATED:
QUALITY CONTROL:
DATED:
RELEASED:
DATED:
CODE:
SIZE:
SCALE:
M
LTR


0.1 uF CAPACITOR FROM U1-20 TO U1-10
0.1 uF CAPACITOR FROM U3-14 TO U3-7
DB-25 MALE PARALLEL PORT CONNECTOR
37A-0* P1 PC-SELDATA
378-0 P2 PC-DATAOUT
378-1 P3 PC-CSOUT
378-2 P4 PC-CLKOUT
378-3 P5 PC-WEOUT
378-4 P6
378-5 P7
378-6 P8
378-7 P9
379-6 P10 PC-CLKIN
379-7* P11 PC-WEIN
379-5 P12 PC-CSIN
379-4 P13 PC-DATAIN
37A-1* P14
379-3 P15
37A-2 P16
37A-3* P17
P1
GND P18
GND P19
GND P20
GND P21
GND P22
GND P23
GND P24
GND P25
U1
74HC244
1G
1A1 1Y1
1A2 1Y2
1A3 1Y3
1A4 1Y4
2G
2A1 2Y1
2A2 2Y2
2A3 2Y3
2A4 2Y4
47
R7
47
R6
U3F
U3E
U3A
U3B
74HC14
C1 .01uF
C2 .01uF
C3 .01uF
C4 .01uF
C5 .01uF
Shottky Diodes
D4
D3
D2
D1
L1 470 uH
C7 22uF
C6 .1uF
R11 1
U2
LX
GND
LBO
LBI
VOUT
CP
VFB
COMP
MAX631ACSA
C9 22uF
C8 .1uF
L2 470 uH
5V
C10 22uF
C11 22uF
C12 22uF
R10
R9
R8 47
R5 open
R4 open
R3 4.7
R2 open
R1 1
MAX1
MAXIM
120 San Gabriel Dr
Sunnyvale, CA 94086
408-7377600
MAX1458 PARALLEL P
Revision: 4.1
July 8, 1998

ALL UNITS ARE IN 0.001"	MAX1478 EVALUATION BOARD			
LAYER COMPONENT SIDE	PROPERTY OF MAXIM INTEGRATED PRODUCTS			
DESIGNER			DRAWING NUMBER	REV A
ENG				
LAYOUT				
RELEASED	SCALE: 1 TO 1	DATE	1 OF	



ALL UNITS ARE IN 0.001"

LAYER SOLDER SIDE

DESIGNER

ENG

LAYOUT

RELEASED

MAX1478 EVALUATION BOARD

PROPERTY OF
MAXIM
INTEGRATED PRODUCTS

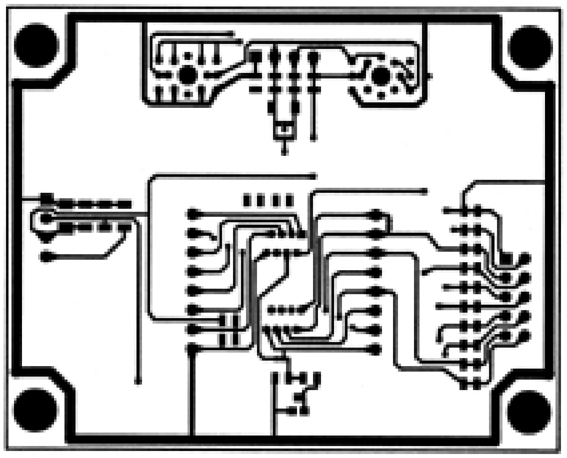
DRAWING NUMBER

REV
A

SCALE: 1 TO 1

DATE

2 OF



ALL UNITS ARE IN 0.001"

MAX1478 EVALUATION BOARD

LAYER TOP SILKSCREEN

PROPERTY OF
MAXIM
INTEGRATED PRODUCTS

DESIGNER

ENG

LAYOUT

RELEASED

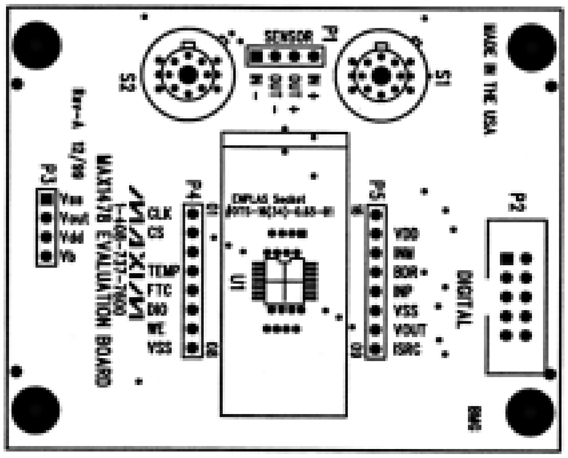
DRAWING NUMBER

REV
A

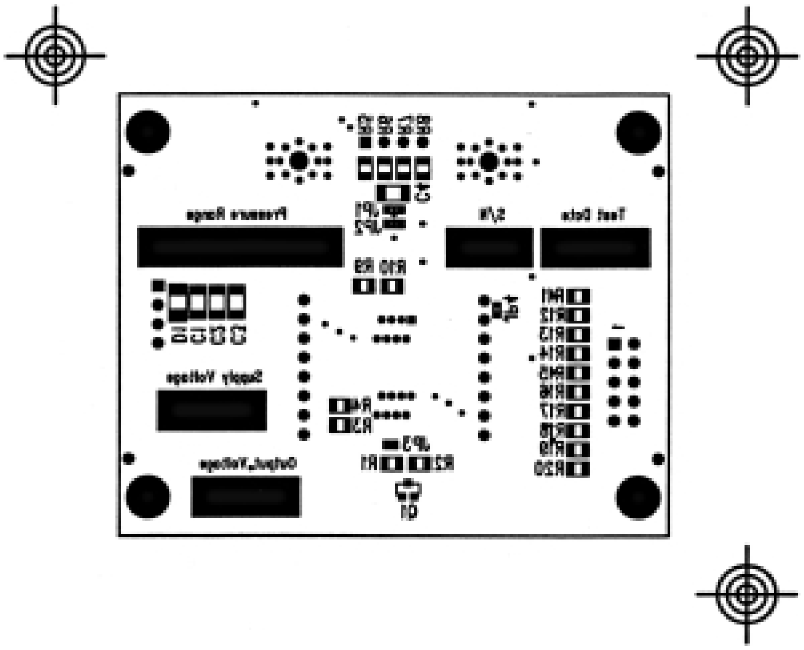
SCALE: 1 TO 1

DATE

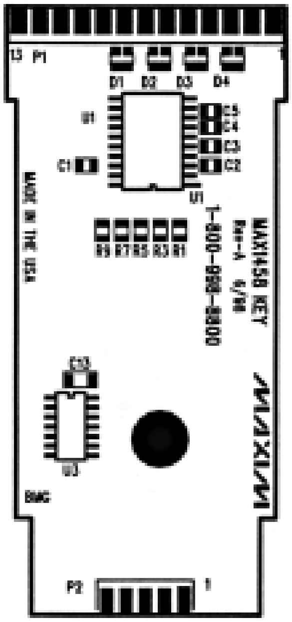
5 of



ALL UNITS ARE IN 0.001"	MAX1478 EVALUATION BOARD	
LAYER BOTTOM SILKSCREEN	PROPERTY OF MAXIM INTEGRATED PRODUCTS	
DESIGNER		
ENG	DRAWING NUMBER	REV A
LAYOUT		
RELEASED	SCALE: 1 TO 1 DATE	7 OF



ALL UNITS ARE IN 0.001"		MAX1458 KEY			
LAYER COMPONENTSCREEN		PROPERTY OF MAXIM INTEGRATED PRODUCTS			
DESIGNER					
ENG				DRAWING NUMBER	REV A
LAYOUT GRENOBLE	49/98				
RELEASED		SCALE: 1 TO 1	DATE	5 OF	



ALL UNITS ARE IN 0.001"

LAYER COMPONENT SIDE

DESIGNER

ENG

LAYOUT GRENOBLE 49/98

RELEASED

MAX1458 KEY

PROPERTY OF
MAXIM
INTEGRATED PRODUCTS

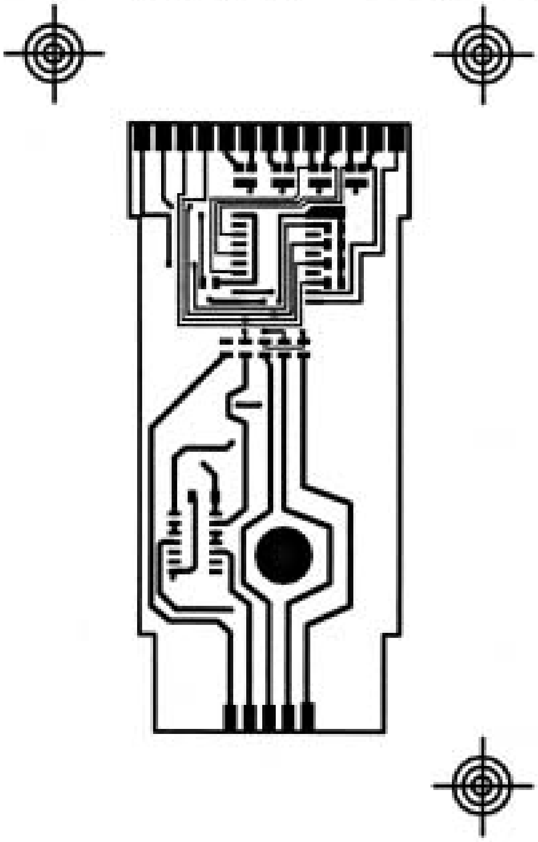
DRAWING NUMBER

REV A

SCALE: 1 TO 1

DATE

1 OF



ALL UNITS ARE IN 0.001"

MAX1458 KEY

LAYER SOLDER SIDE

PROPERTY OF
MAXIM
INTEGRATED PRODUCTS

DESIGNER

ENG

LAYOUT GRENOBLE 49/98

RELEASED

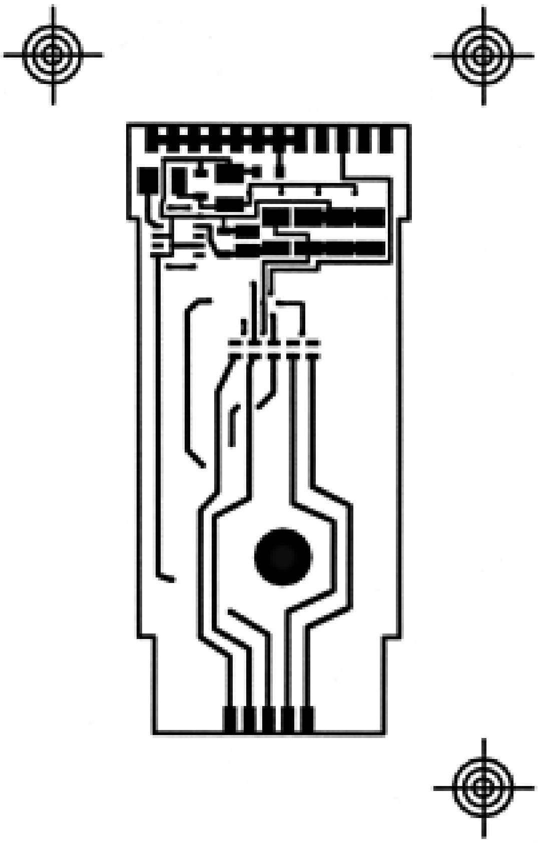
DRAWING NUMBER

REV A

SCALE: 1 TO 1

DATE

2 OF



REPLACING THE SENSOR

The factory-calibrated sensor may be replaced by a user-provided sensor. The circuit board has hole patterns that support a wide range of commercially available piezoelectric sensors. The sensor may be mounted on the circuit board or may be connected remotely using I/O connector P1. The new sensor should be calibrated in a temperature-controlled environmental chamber.

Pin	Signal	Description
1	IN-	Bottom of Wheatstone Bridge
2	OUT-	Sensor Negative Output
3	OUT+	Sensor Positive Output
4	IN+	Top of Wheatstone Bridge

Table 12-5

I/O Connector P1 Signals - Sensor Interface

Pin	Signal	Description
1	VSS	Ground return
2	VOUT	Output Voltage
3	VDD	Positive power supply rail, +5V
4	BDRIVE	Voltage at top of Wheatstone Bridge (proportional to Temp.)
5	VSS	Ground return
6	CS	Chip-select to MAX1478
7	ECLK	Serial Clock
8	DI/O	Serial data input/output
9	INP	Sensor positive output
10	INM	Sensor negative output

Table 12-6

I/O Connector P2 Signals - Digital Interface

Pin	Signal	Description
1	VSS	Ground return
2	VOUT	Output Voltage
3	VDD	Positive power supply rail, +5V
4	BDRIVE	Voltage at top of Wheatstone Bridge.

Table 12-7

I/O Connector P3 Signals - Analog Interface

Jumper	State	Function
JP1	1-2 *	Normal sensor polarity
JP1	2-3	Reverse sensor polarity
JP2	1-2 *	Normal sensor polarity
JP2	2-3	Reverse sensor polarity
JP3	open *	Temp bypass, leave open.
JP4	open	Use with metal film strain gauge, Q1 diode junction senses temperature

Table 12-8

Jumper Function Table

**** Asterisk indicates default jumper state***

EV KIT TEST PROCEDURE

CONTENTS OF THE MAX1478 EVALUATION KIT

The MAX1478EVKIT Evaluation Kit is shipped fully temperature-compensated by the factory from -40°C to +125°C. Components of this EV KIT are not available separately, except for the MAX1478 Reference Manual and the MAX1458/78KEY interface adapter. Additional material may be included in your Evaluation Kit which is not listed below.

1. Compensated MAX1478 Evaluation Board with a sensor
2. Computer interface adapter for IBM-PC parallel port
3. Computer interface adapter ribbon interconnect cable
4. 3_ " IBM-PC compatible program and data disk
5. This MAX1478 REFERENCE MANUAL
6. Printout of compensation test data
7. 5 samples of the MAX1478

OVERVIEW

The purpose of this kit is to demonstrate the capability of the MAX1478 in compensating a typical piezoresistive sensor to within 1% of its inherent repeatability limitations. To assist the user to quickly evaluate the ASIC, the board has been precompensated at Maxim Integrated Products using a generic low-pressure sensor such as the Lucas NovaSensor model NPH8-100G pressure sensor. An equivalent sensor from another manufacturer may also be substituted.

The second objective of the kit is to allow the user to learn how to program the ASIC using a hands-on approach. To do this, the user is encouraged to compensate his/her own sensor using the evaluation kit along with the instructions provided. This kit is intended to be used by engineers familiar with silicon piezoresistive sensors and their compensation techniques.

The test data printout is included in the EVKIT. This data is specific to the particular EKVIT PCB enclosed in the KIT. Both the spreadsheet printout and the EVKIT will contain a serial number for unique identification.

UNPACKING

Carefully remove the evaluation kit from out of the anti-static bag. **CAUTION:** This is a precision calibrated device; the sensor calibration may be affected by excessive force on its case. Do not remove the sensor’s plastic protector (if supplied) until the moment that the test port tubing is to be connected. Unpack the communications adapter and ribbon cable; set them aside, as they will not be required for the initial tests. It is not required that the user completely read this Reference Manual to test the board. However, this Reference Manual will have to be read before the user can compensate his/her own sensor.

EQUIPMENT NEEDED

Maxim recommends that the user first test the pre-compensated evaluation board before any attempt is made to reprogram the MAX1478. The initial test will **not** require a computer, since the module is already compensated. The user only needs to supply power to the PCB and measure the output voltage as a function of pressure and temperature. The following equipment will be needed to test the precompensated module:

1. A precision-regulated power supply capable of providing +5.000 volts.
2. A multimeter with at least 5 significant digits.
3. A 0-15 psi gauge pneumatic pressure controller/calibrator.
4. A source of dry air or nitrogen.
5. An environmental chamber capable of -40 to +125°C, **non-condensing.**

Later on, when the user is ready to experiment with reprogramming the MAX1478, the following additional equipment will be needed.

1. An IBM-PC compatible computer running Windows 95/98.
2. A second DVM or a 2-channel switch box.

EXPLANATION OF THE TEST RESULTS

It is important to take a moment to explain the test data. Each evaluation kit comes with specific test data taken at Maxim before shipment. This consists of an Excel spreadsheet file with all the test data. Both a hardcopy of the data and the data file itself are included.

Compensation of the evaluation board was performed using two test temperatures. The sensor characteristics were measured at each temperature through the ASIC signal path and the device was immediately compensated at that temperature. The compensation accuracy is usually better than 1 % over the sensor's repeatability errors.

After the device is programmed, a final test is performed after the module is allowed to 'relax' at room temperature for a minimum of one day. This retest is performed to measure the total error, primarily the sensor non-repeatability errors. This final test is referred to as the Device Characterization. During Device Characterization, the device output voltage, sensor output, and sensor Excitation are measured for each of three pressures: Pmin, Pmid, and Pmax. This data is displayed in the graph titled "Module characterization error."

INITIAL SETUP

Refer to the MAX1478 Evaluation Board Figure 13-1 when locating the connectors. The Sensor connector is a four-pin SIP-type connector which can be used to probe the four sensor nodes, sensor excitation “IN+”, sensor ground “IN-“, sensor positive output “OUT+”, and sensor negative output “OUT-“. Later on, if the user wishes to remove the sensor mounted on the board, this connector may serve as a means of wiring the user’s own sensor. The digital connector at the top is used to connect the board to the interface adapter, which allows the user to reprogram the ASIC via the computer. The Analog connector allows the user to supply power to the board and to measure the output voltage and the sensor excitation voltage. Note that all the connectors and test pins are labeled on the board.

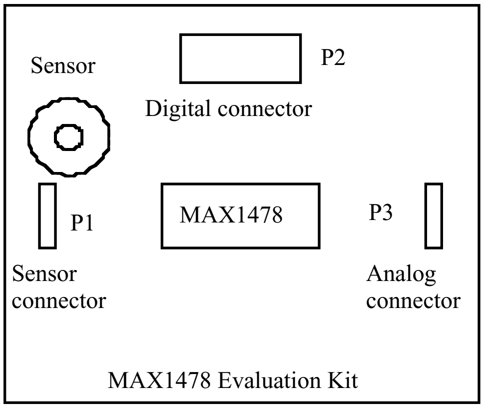


Figure 13-1

Layout of the Evaluation Board

The first step is to perform a room-temperature bench test of the circuit. The output of the board is ratiometric to the supply; therefore, a very accurate setting of the supply voltage is required to minimize measurement errors. Also, the board contains a Zener diode which will help protect the board against overvoltage and reverse voltage. The protection circuit will be enabled if the supply becomes less than about -0.7 volts, or more than about +6.2 volts. The initial electrical connections should be as follows:

1. Connect the negative terminal of the power supply to the Analog connector pin labeled “VSS”.
2. Connect the positive terminal of the power supply to the Analog connector pin labeled “VDD”.
3. Connect the DVM to the Analog connector pin labeled “VOUT”; the ground return should be connected to the Analog connector pin labeled “VSS”.

IMPORTANT! To avoid problems with ground loops, noise, and to prevent possible damage to the MAX1458KEY adapter, connect all equipment including the computer (used later) to the same AC circuit and use one common earth ground. If the power supply has programmable current limit, set it to about 10mA. Adjust the supply voltage to +5.000V and measure the voltage at test point “VDD” with respect to test point “VSS”. At this point, there should be no connection to the sensor pressure port. Since the sensor supplied is a “Gauge” type, the output voltage at the Analog connector should be reading about 0.5V.

The next step is a room-temperature pressure test. Carefully remove the plastic sensor protector (if supplied) and connect a silicone pressure tube to the sensor pressure port. **Grasp the sensor** (not the PCB) while fitting the tube in place. Perform any required pressure controller initialization/calibration procedures, then vent the system. The output voltage should read 0.500 volts. Perform a few pressure cycles to minimize hysteresis effects. Apply full-scale pressure as stated in the test data or as written on the back of the board, and confirm that the output reads 4.500 volts. The user may also test at other lesser pressures to check for pressure linearity errors.

After these steps are completed, the next step is to put the board in the environmental chamber and test the board over any temperatures between –40 and +125°C. It is advisable to first perform one or two full excursions of temperature and pressure to minimize hysteresis errors. Maxim recommends that the electronics be conformal coated in any application where condensation of moisture may occur. This was **not** done to the evaluation boards, since the user may wish to modify the circuit for his/her own specific requirements.

Since the PCB is not conformal coated, it is important that the environmental chamber **not** allow condensation to take place. If this should happen, Maxim recommends a bake-out at +125°C (with no power applied) for a minimum of one hour. Note that the circuit may behave erratically if moisture is allowed to condense on the circuit board, since weak ionic paths will affect some high impedance nodes on the board.

Most of the error after compensation is due to the sensor drift and non-repeatable behavior. So the customer can understand the source of these errors, we have provided the low-level sensor output that was measured during compensation at each temperature. The user may wish to compare this data with his/her measurements of the sensor output in order to separate sensor errors from ASIC errors. This can be performed at the “Sensor connector.” To avoid attenuating the sensor output signal, Maxim recommends using a multimeter with an input impedance of **greater than 10MΩ** for this measurement.

COMPUTER REQUIREMENTS AND CONNECTIONS

The next logical step after checking the module performance is to actually edit, and reprogram the module using the same sensor. Before this can be done, however, we must connect the digital interface to the computer. Below is a list of the computer requirements:

1. IBM compatible PC
2. Windows 95/98
3. 1 unused parallel printer port
4. Mouse
5. 3_ “ Disk drive

ABOUT THE INTERFACE ADAPTER

The MAX1478 requires one digital line for driving its chip select. Additionally, two more digital lines are required for communication. The Interface Adapter contains buffers to allow digital lines from the parallel port to communicate with the ASIC. Also in the adapter, there is a monolithic charge pump voltage converter which generates the power for the interface adapter’s circuitry from the parallel port output lines.

The adapter operates internally at 5 volts; therefore, ratiometricity tests of the evaluation board should be limited to 4.5 - 5.5 volts while the digital connector is in place. This is to prevent logic-level mismatch and also to prevent biasing protection diodes in the front end of the digital circuits.

INSTALLING AND TESTING THE SOFTWARE

The MAX1478 EVKit software is an executable developed using National Instrument’s LabView ® Software. LabView® is not required to run the executable. The software is a high-level interface that includes a low-level evdll.dll.

A 3_ “ distribution disk is included. Below is a listing of the disk contents. The letter “X” symbolizes where the module serial number will be appended to the filename. There may be other files on the disk not mentioned here; if so, they will be described in file “read.me” which can be read from any text editor. This “read.me” file, if present, may also contain last minute information or updates.

1.	“MAX1478.exe”	Communication program
2.	“comp-XXX.xls”	Excel Spreadsheet data file
3.	“eepromXX.prn”	EEPROM contents
4.	“read.me”	Optional file containing last minute additions

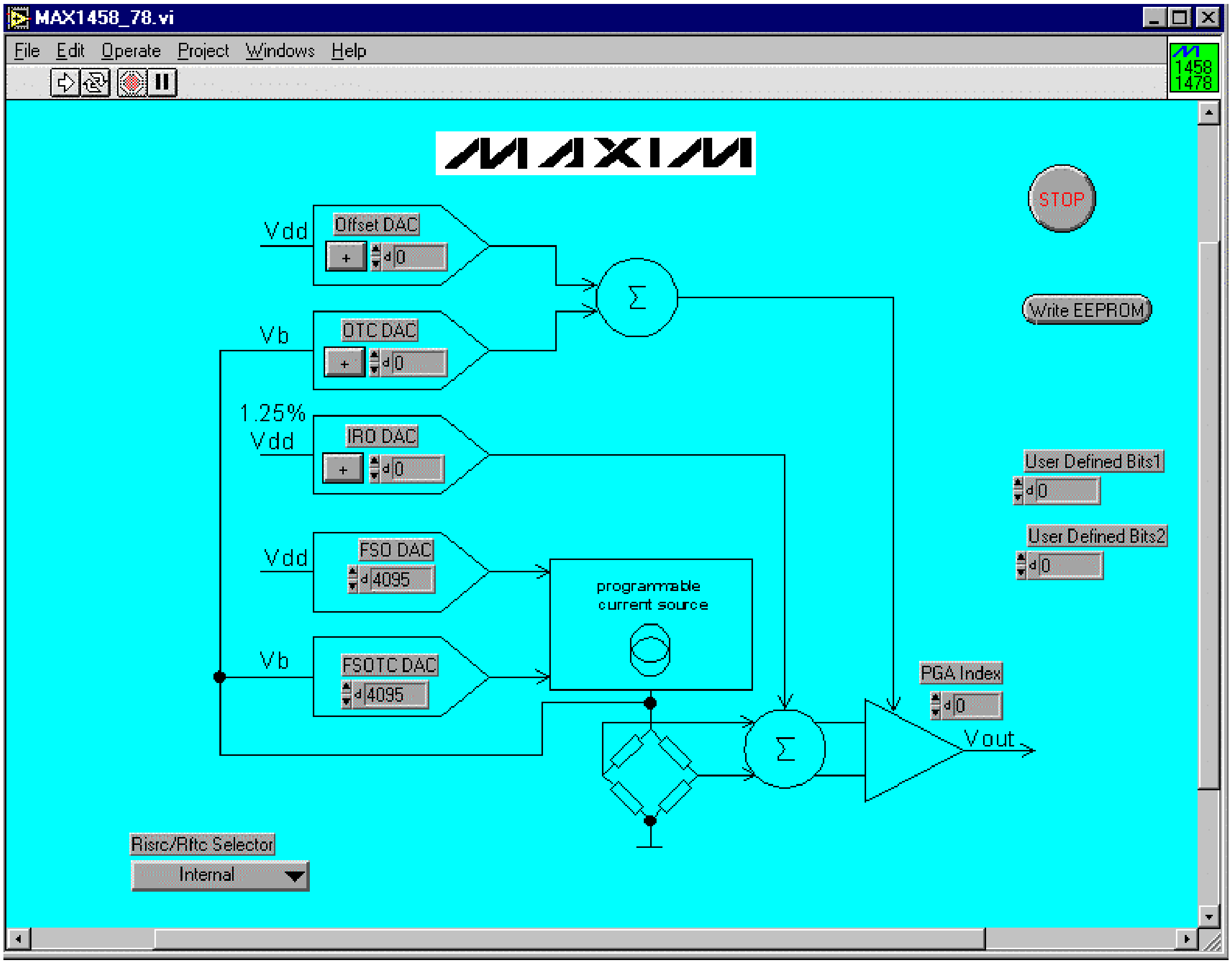
To begin, locate an unused parallel port on the back of the computer. If one is not found, temporarily disconnect the printer from the computer and use that port. Connect the interface adapter to an unused parallel port and note the address (LPT1:, LPT2:, or LPT3:). Do not connect the ribbon cable to the interface adapter yet.

Power up the Evaluation board as before, via the ”Analog connector”. Connect the keyed color-coded ribbon cable from the back of the computer interface adapter to the MAX1478 Evaluation board “Digital connector”.

Install the software in a separate directory. Double-click on the MAX1478.exe program. Upon entering the program, the software will first read in the EEPROM contents so it can display current “fresh” data. If the ASIC is not connected, an error will occur. The software allows editing the contents of the ASIC’s registers and EEPROM and observing the effects on the output. Once desired results are obtained, the EEPROM can be programmed with the register contents.

The software allows editing the following:

- Coarse Offset (IRO DAC)
- Fine Offset
- Offset TC value and sign
- Span
- Span TC
- PGA Gain
- User bits
- Risrc/Rftc selection



Offset DAC 0
OTC DAC 0
IRO DAC 0
FSO DAC 4095
FSOTC DAC 4095
User Defined Bits1 0
User Defined Bits2 0
PGA Index 0
Rlsrc/Rftc Selector Internal

Figure 12-1

MAX1478.exe Interface

Editing values is a simple matter of selecting the input parameter to be edited by pointing at it with the mouse and clicking either on the up/down arrows or entering the value desired. In the case of the button-operated parameters, clicking the button is all that is required. Once the data has been entered, the software will display the modified output parameters.

When the user is satisfied with the register values, he/she can program the EEPROM by clicking the “WRITE EEPROM” button. The software always performs a write/read verify. A message will be displayed to indicate if the write was successful or not. EEPROM programming should only be executed at room temperature (25°C)

PROGRAMMING THE MAX1478

Although no harm can come from the user experimenting with the communication software, we strongly recommend that the user take time to read the MAX1478 Application Manual before proceeding. An understanding of the MAX1478 architecture is essential before proceeding any further.

Begin by experimenting with the offset voltage. The best way to do this is to select the offset register and then increment or decrement the value. Since the DACs have a very fine resolution (16 bits), a change of only one or two digits will probably go unnoticed if the user is looking at Vout, unless the DVM has a very high resolution. If attempting to measure the voltage at the DAC output nodes, a DVM with a 10,000MΩ input impedance is required so as not to load down these high-impedance nodes. Next change the Sensor Excitation current by editing the Span register in a similar manner as the offset register. A change to the Span register will necessitate a readjustment of the offset. A recommended exercise would be for the user to reprogram the span or offset of the module, and retest it over temperature.

INSTALLING THE USER SENSOR

One should be very familiar with the basic operation of the ASIC and the software before attempting to remove the sensor supplied with the board and replacing it with the user sensor. Four generic sensor footprints have been provided on the PCB for the most popular “Metal Can” sensor packages. The MAX1478 works with 4-wire closed Wheatstone Bridge-configured sensors. If the sensor cannot be mounted on the PCB, it may be connected to the generic 4-pin “Sensor” SIP connector. The sensor pinouts have been previously identified.

Alternately, the user may test the ASIC using an artificial bridge consisting of four surface-mount resistors, with the pads located to the right of the sensor connector. Some general knowledge of the user’s sensor parameters must be known in order to set the initial coefficients. In this way, the ASIC will not be overloaded, i.e., output saturated. It is recommended that the sensor wires be kept as short as possible to minimize system noise. At this point, the user is referred to the section titled “Compensation Procedure” in the MAX1478 Application Manual for a step-by-step procedure for compensating their sensor.

FREQUENTLY ASKED QUESTIONS

Upon Startup, the program is unable to locate the interface KEY.

- Verify the KEY is plugged into a free parallel port.

The program cannot communicate with the MAX1478 or does so unreliably.

- The EV KIT requires its own 5V external user-supplied power. Verify that 5 volts are present on the analog connector.
- Insure that ALL test equipment being used is connected to a single terminal strip and grounded together.
- Verify the interface cable is connected properly and is not damaged. Perform a cable continuity check. Do not lengthen the cable beyond a total of 5 feet. Do not add an extension cable between the parallel port connector on the computer and the interface adapter (KEY).

The sensor voltage and/or output voltage jump erratically.

- Moisture condensation in the test oven may cause this problem. Purge with dry air or nitrogen.

I altered the EEPROM contents and would like to restore the factory settings.

- Rewrite the factory-set coefficients into EEPROM. The coefficients are found in the file “eepromxx.prn”, where xx is the serial number of the board.

The output of the board is noisy.

- Keep the sensor wires as short as possible, especially when operating at the higher gain settings. Add a bypass capacitor across the sensor output lines.

- If using an external sensor, use shielded cables between the sensor and the ASIC.

- If the interface adapter is connected, verify all equipment is properly grounded as recommended.

Can I obtain the Source Code for the communications program?

- Yes. The MAX1478 EV KIT software is written in LabView. Although LabView is not required to use the software, it is required to view the source code and make changes. Contact the factory for further details.

Is the MAX1478KEY a security device?

- No. However, the software will not operate without a MAX1478 connected to it because it will not be able to read the EEPROM.

Can I obtain additional MAX1478KEY adapters?

- Yes. The interface adapters can be purchased separately; contact the factory for more details.

Will Maxim make custom modifications to the MAX1478 to better suit my application?

- Yes. The ASIC can be modified for an N.R.E. fee and/or a production order commitment. Contact the factory.

What is transistor Q1 in the EV KIT used for?

- A transistor has been added to the current source reference to increase the ∆Vbridge signal over temperature. A fundamental requirement of the MAX1478 architecture is that the sensor’s TCR (Temperature Coefficient of Resistance) be greater than TCS (Temperature Coefficient of Sensitivity). Where this is not the case, the transistor must be added as shown. For most applications, this transistor can be removed (tie the emitter to the collector).

Why does my test data differ slightly from the factory data?

- The calibration of the board is valid over the specified temperature range of -40°C to +125°C for steady-state temperatures so the board and all its components, as well as the sensor, are at the same uniform temperature. A minimum of 15 minutes of temperature soak time is recommended at each temperature before taking calibration measurements. An alternate method is to monitor Vbridge (since it is proportional to temperature), and wait until is reaches a steady-state condition. Sensor repeatability also has a negative effect on compensation accuracy verification.

Can I lengthen the interface adapter cable?

- Generally not, or not without caution. A five-foot long ribbon cable has been supplied in order to allow the board to be connected to the computer via the Interface Adapter. Do not increase the length of this cable, as this may compromise the data integrity of the digital bus.

What can I do to minimize sensor repeatability errors on the EV KIT?

- Sensor parameters may change over time or during shipment. The sensor offset is notorious for drifting over time. A sensor “wake up” is recommended before precise calibration measurements can be taken. This “wake up” should include several full-temperature excursions, combined with full-scale pressure excursions. Calibration data provided includes the low-level sensor output as measured by Maxim during compensation. The user may wish to take similar readings, at the same temperatures, to determine if any sensor changes have occurred. The difference in low-level sensor output readings between Maxim and the user’s readings can be multiplied by the ASIC signal path gain to predict the error at the output of the module. The usual PGA gain setting is A=90. Check the signal path PGA setting on your particular module for the actual gain used.

MISCELLANEOUS

SENSOR DATA SHEET

The MAX1478 Evaluation Kit contains a generic sensor manufactured by Lucas NovaSensor, Inc., Fremont, CA. The attached information was obtained from, and is posted on the internet at location:

http://www.novasensor.com