

# AN1316

## Frequency Output Conversion for MPX2000 Series Pressure Sensors

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### INTRODUCTION

Typically, a semiconductor pressure transducer converts applied pressure to a "low-level" voltage signal. Current technology enables this sensor output to be temperature compensated and amplified to higher voltage levels on a single silicon integrated circuit (IC). While on-chip temperature compensation and signal conditioning certainly provide a significant amount of added value to the basic sensing device, one must also consider how this final output will be used and/or interfaced for further processing. In most sensing systems, the sensor signal will be input to additional analog circuitry, control logic, or a microcontroller unit (MCU).

MCU-based systems have become extremely cost effective. The level of intelligence which can be obtained for only a couple of dollars, or less, has made relatively simple 8-bit microcontrollers the partner of choice for semiconductor pressure transducers. In order for the sensor to communicate its pressure-dependent voltage signal to the microprocessor, the MCU must have an analog-to-digital converter (A/D) as an on-chip resource or an additional IC packaged A/D. In the

latter case, the A/D must have a communications interface that is compatible with one of the MCU's communications protocols. MCU's are adept at detecting logic-level transitions that occur at input pins designated for screening such events. As an alternative to the conventional A/D sensor/MCU interface, one can measure either a period (frequency) or pulse width of an incoming square or rectangular wave signal. Common MCU timer subsystem clock frequencies permit temporal measurements with resolution of hundreds of nanoseconds. Thus, one is capable of accurately measuring the the frequency output of a device that is interfaced to such a timer channel. If sensors can provide a frequency modulated signal that is linearly proportional to the applied pressure being measured, then an accurate, inexpensive (no A/D) MCU-based sensor system is a viable solution to many challenging sensing applications. Besides the inherent cost savings of such a system, this design concept offers additional benefits to remote sensing applications and sensing in electrically noisy environments.

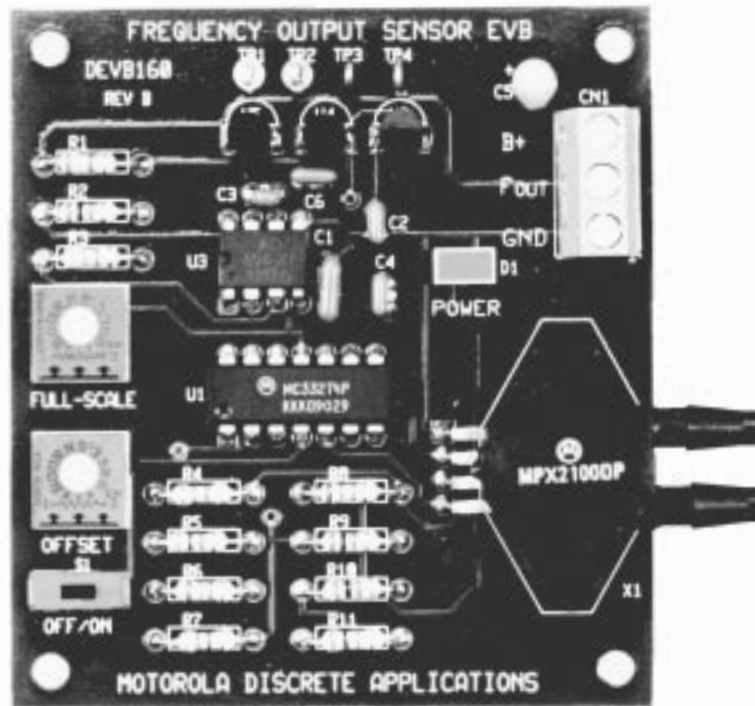


Figure 1. DEVB160 Frequency Output Sensor EVB

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The following sections will detail the design issues involved in such a system architecture, and will provide an example circuit which has been developed as an evaluation tool for frequency output pressure sensor applications.

### DESIGN CONSIDERATIONS

#### Signal Conditioning

Motorola's MPX2000 Series sensors are temperature compensated and calibrated – i.e. – offset and full-scale span are precision trimmed – pressure transducers. These sensors are available in full-scale pressure ranges from 10 kPa (1.5 psi) to 200 kPa (30 psi). Although the specifications in the data sheets apply only to a 10 V supply voltage, the output of these devices is ratiometric with the supply voltage. At the absolute maximum supply voltage specified, 16 V, the sensor will produce a differential output voltage of 64 mV at the rated full-scale pressure of the given sensor. One exception to this is that the full-scale span of the MPX2010 (10 kPa sensor) will be only 40 mV due to a slightly lower sensitivity. Since the maximum supply voltage produces the most output voltage, it is evident that even the best case scenario will require some signal conditioning to obtain a usable voltage level.

Many different “instrumentation-type” amplifier circuits can satisfy the signal conditioning needs of these devices. Depending on the precision and temperature performance demanded by a given application, one can design an amplifier circuit using a wide variety of operational amplifier (op amp) IC packages with external resistors of various tolerances, or a precision-trimmed integrated instrumentation amplifier IC. In any case, the usual goal is to have a single-ended supply, “rail-to-rail” output (i.e. use as much of the range from ground to the supply voltage as possible, without saturating the op amps). In addition, one may need the flexibility of performing zero-pressure offset adjust and full-scale pressure calibration. The circuitry or device used to accomplish the voltage-to-frequency conversion will determine if, how, and where calibration adjustments are needed. See Evaluation Board Circuit Description section for details.

#### Voltage-to-Frequency Conversion

Since most semiconductor pressure sensors provide a voltage output, one must have a means of converting this voltage signal to a frequency that is proportional to the sensor output voltage. Assuming the analog voltage output of the sensor is proportional to the applied pressure, the resultant

frequency will be linearly related to the pressure being measured. There are many different timing circuits that can perform voltage-to-frequency conversion. Most of the “simple” (relatively low number of components) circuits do not provide the accuracy or the stability needed for reliably encoding a signal quantity. Fortunately, many voltage-to-frequency (V/F) converter IC's are commercially available that will satisfy this function.

#### Switching Time Reduction

One limitation of some V/F converters is the less than adequate switching transition times that effect the pulse or square-wave frequency signal. The required switching speed will be determined by the hardware used to detect the switching edges. The Motorola family of microcontrollers have input-capture functions that employ “Schmitt trigger-like” inputs with hysteresis on the dedicated input pins. In this case, slow rise and fall times will not cause an input capture pin to be in an indeterminate state during a transition. Thus, CMOS logic instability and significant timing errors will be prevented during slow transitions. Since the sensor's frequency output may be interfaced to other logic configurations, a designer's main concern is to comply with a worst-case timing scenario. For high-speed CMOS logic, the maximum rise and fall times are typically specified at several hundreds of nanoseconds. Thus, it is wise to speed up the switching edges at the output of the V/F converter. A single small-signal FET and a resistor are all that is required to obtain switching times below 100 ns.

### APPLICATIONS

Besides eliminating the need for an A/D converter, a frequency output is conducive to applications in which the sensor output must be transmitted over long distances, or when the presence of noise in the sensor environment is likely to corrupt an otherwise healthy signal. For sensor outputs encoded as a voltage, induced noise from electromagnetic fields will contaminate the true voltage signal. A frequency signal has greater immunity to these noise sources and can be effectively filtered in proximity to the MCU input. In other words, the frequency measured at the MCU will be the frequency transmitted at the output of a sensor located remotely. Since high-frequency noise and 50–60 Hz line noise are the two most prominent sources for contamination of instrumentation signals, a frequency signal with a range in the low end of the kHz spectrum is capable of being well filtered prior to being examined at the MCU.

Table 1. Specifications

| Characteristics      | Symbol            | Min | Typ               | Max | Units   |
|----------------------|-------------------|-----|-------------------|-----|---------|
| Power Supply Voltage | B <sup>+</sup>    | 10  |                   | 30  | Volts   |
| Full Scale Pressure  | P <sub>FS</sub>   |     |                   |     |         |
| – MPX2010            |                   |     |                   | 10  | kPa     |
| – MPX2050            |                   |     |                   | 50  | kPa     |
| – MPX2100            |                   |     |                   | 100 | kPa     |
| – MPX2200            |                   |     |                   | 200 | kPa     |
| Full Scale Output    | f <sub>FS</sub>   |     | 10                |     | kHz     |
| Zero Pressure Offset | f <sub>OFF</sub>  |     | 1                 |     | kHz     |
| Sensitivity          | S <sub>AOUT</sub> |     | 9/P <sub>FS</sub> |     | kHz/kPa |
| Quiescent Current    | I <sub>CC</sub>   |     | 55                |     | mA      |

## EVALUATION BOARD

The following sections present an example of the signal conditioning, including frequency conversion, that was developed as an evaluation tool for the Motorola MPX2000 series pressure sensors. A summary of the information required to use evaluation board number DEVB160 is presented as follows.

### Description

The evaluation board shown in Figure 1 is designed to transduce pressure, vacuum or differential pressure into a single-ended, ground referenced voltage that is then input to a voltage-to-frequency converter. It nominally provides a 1 kHz output at zero pressure and 10 kHz at full scale pressure. Zero pressure calibration is made with a trimpot that is located on the lower half of the left side of the board, while the full scale output can be calibrated via another trimpot just above the offset adjust. The board comes with an MPX2100DP sensor installed, but will accommodate any MPX2000 series sensor. One additional modification that may be required is that the gain of the circuit must be increased slightly when using an MPX2010 sensor. Specifically, the resistor R5 must be increased from 7.5 kΩ to 12 kΩ.

### Circuit Description

The following pin description and circuit operation corresponds to the schematic shown in Figure 2.

### Pin-by-Pin Description

#### B<sup>+</sup>:

Input power is supplied at the B<sup>+</sup> terminal of connector CN1. Minimum input voltage is 10 V and maximum is 30 V.

#### F<sub>out</sub>:

A logic-level (5 V) frequency output is supplied at the OUT terminal (CN1). The nominal signal it provides is 1 kHz at zero

pressure and 10 kHz at full scale pressure. Zero pressure frequency is adjustable and set with R12. Full-scale frequency is calibrated via R13. This output is designed to be directly connected to a microcontroller timer system input-capture channel.

#### GND:

The ground terminal on connector CN1 is intended for use as the power supply return and signal common. Test point terminal TP3 is also connected to ground, for measurement convenience.

#### TP1:

Test point 1 is connected to the final frequency output, F<sub>out</sub>.

#### TP2:

Test point 2 is connected to the +5 V regulator output. It can be used to verify that this supply voltage is within its tolerance.

#### TP3:

Test point 3 is the additional ground point mentioned above in the GND description.

#### TP4:

Test point 4 is connected to the +8 V regulator output. It can be used to verify that this supply voltage is within its tolerance.

#### P1, P2:

Pressure and Vacuum ports P1 and P2 protrude from the sensor on the right side of the board. Pressure port P1 is on the top (marked side of package) and vacuum port P2, if present, is on the bottom. When the board is set up with a dual ported sensor (DP suffix), pressure applied to P1, vacuum applied to P2 or a differential pressure applied between the two all produce the same output voltage per kPa of input. Neither port is labeled. Absolute maximum differential pressure is 700 kPa.

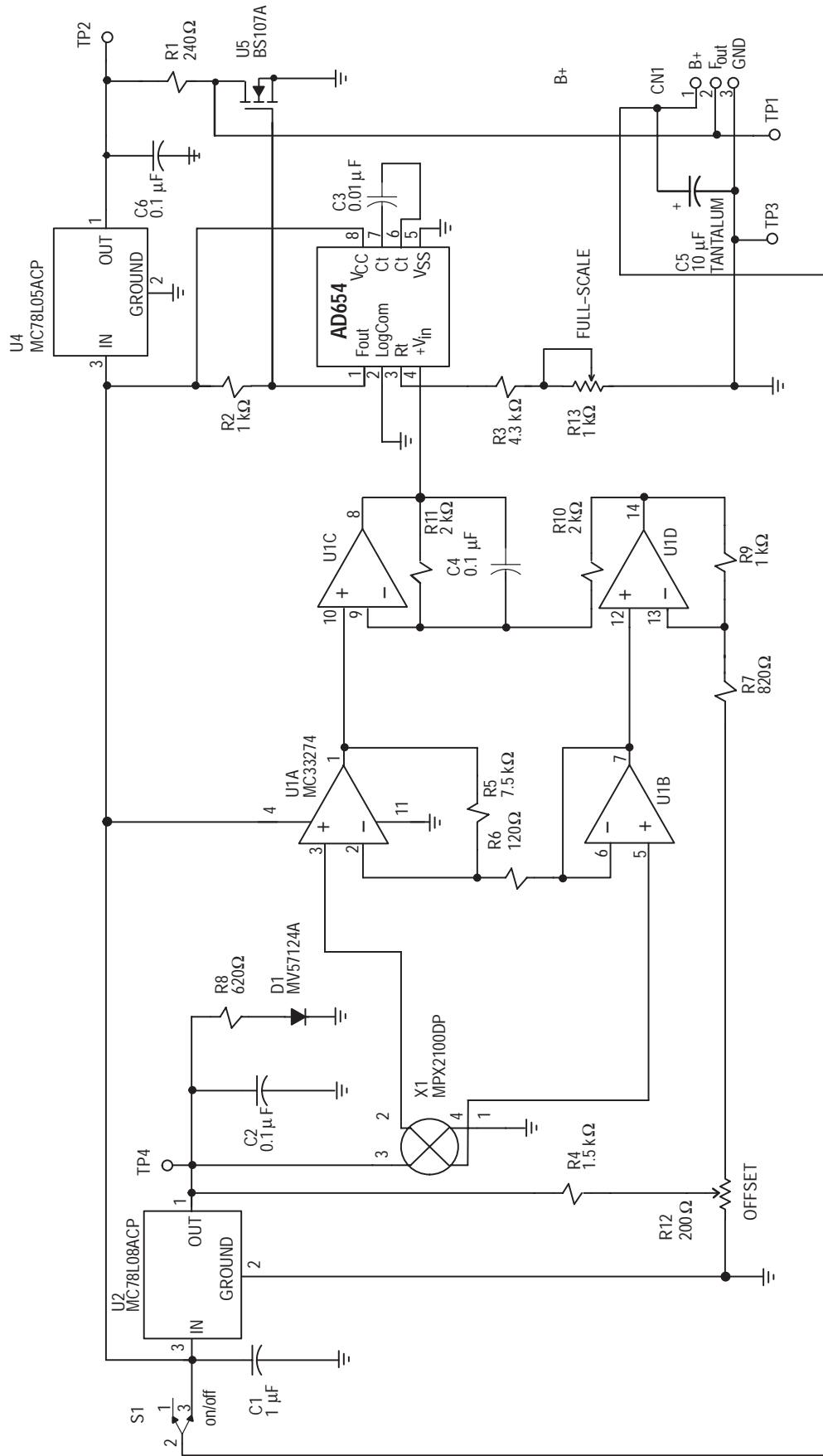


Figure 2. DEVB160 Frequency Output Sensor Evaluation Board

The following is a table of the components that are assembled on the DEVB160 Frequency Output Sensor Evaluation Board.

**Table 2. Parts List**

| Designators | Quantity | Description             | Manufacturer   | Part Number  |
|-------------|----------|-------------------------|----------------|--------------|
| C1          | 1        | 1 $\mu$ F Capacitor     |                |              |
| C2          | 1        | 0.1 $\mu$ F Capacitor   |                |              |
| C3          | 1        | 0.01 $\mu$ F Capacitor  |                |              |
| C4          | 1        | 0.1 $\mu$ F Capacitor   |                |              |
| C5          | 1        | 10 $\mu$ F Cap+         |                | tantalum     |
| C6          | 1        | 0.1 $\mu$ F Capacitor   |                |              |
| CN1         | 1        | .15LS 3 Term            | PHX Contact    | 1727023      |
| D1          | 1        | RED LED                 | Quality Tech.  | MV57124A     |
| R1          | 1        | 240 $\Omega$ resistor   |                |              |
| R2, R9      | 2        | 1 k $\Omega$ resistor   |                |              |
| R3          | 1        | 4.3 k $\Omega$ resistor |                |              |
| R4          | 1        | 1.5 k $\Omega$ resistor |                |              |
| R5          | 1        | 7.5 k $\Omega$ resistor |                |              |
| R6          | 1        | 120 $\Omega$ resistor   |                |              |
| R7          | 1        | 820 $\Omega$ resistor   |                |              |
| R8          | 1        | 620 $\Omega$ resistor   |                |              |
| R10, R11    | 2        | 2 k $\Omega$ resistor   |                |              |
| R12         | 1        | 200 $\Omega$ Trimpot    | Bourns         | 3386P-1-201  |
| R13         | 1        | 1 k $\Omega$ Trimpot    | Bourns         | 3386P-1-102  |
| S1          | 1        | SPDT miniature switch   | NKK            | SS-12SDP2    |
| TP1         | 1        | YELLOW Testpoint        | Control Design | TP-104-01-04 |
| TP2         | 1        | BLUE Testpoint          | Control Design | TP-104-01-06 |
| TP3         | 1        | BLACK Testpoint         | Control Design | TP-104-01-00 |
| TP4         | 1        | GREEN Testpoint         | Control Design | TP-104-01-05 |
| U1          | 1        | Quad Op Amp             | Motorola       | MC33274      |
| U2          | 1        | 8 V Regulator           | Motorola       | MC78L08ACP   |
| U3          | 1        | AD654                   | Analog Devices | AD654        |
| U4          | 1        | 5 V Regulator           | Motorola       | MC78L05ACP   |
| U5          | 1        | Small-Signal FET        | Motorola       | BS107A       |
| X1          | 1        | Pressure Sensor         | Motorola       | MPX2100DP    |

NOTE: All resistors are 1/4 watt, 5% tolerance values. All capacitors are 50 V rated,  $\pm$ 20% tolerance values.

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### Circuit Operation

The voltage signal conditioning portion of this circuit is a variation on the classic instrumentation amplifier configuration. It is capable of providing high differential gain and good common-mode rejection with very high input impedance; however, it provides a more user friendly method of performing the offset/bias point adjustment. It uses four op amps and several resistors to amplify and level shift the sensor's output. Most of the amplification is done in U1A which is configured as a differential amplifier. Unwanted current flow through the sensor is prevented by buffer U1B. At zero pressure the differential voltage from pin 2 to pin 4 on the sensor has been precision trimmed to essentially zero volts. The common-mode voltage on each of these nodes is 4 V (one-half the sensor supply voltage). The zero pressure output voltage at pin 1 of U1A is then 4.0 V, since any other voltage would be coupled back to pin 2 via R5 and create a non-zero bias across U1A's differential inputs. This 4.0 V zero pressure DC output voltage is then level translated to the desired zero pressure offset voltage by U1C and U1D. The offset voltage is produced by R4 and adjustment trimpot R12. R7's value is such that the total source impedance into pin 13 is approximately 1 k. The gain is approximately  $(R5/R6)(1 + R11/R10)$ , which is 125 for the values shown in Figure 2. A gain of 125 is selected to provide a 4 V span for 32 mV of full-scale sensor output (at a sensor supply voltage of 8 V).

The resulting .5 V to 4.5 V output from U1C is then converted by the V/F converter to the nominal 1–10 kHz that has been specified. The AD654 V/F converter receives the amplified sensor output at pin 8 of op amp U1C. The full-scale frequency is determined by R3, R13 and C3 according to the following formula:

$$F_{\text{out}} (\text{full-scale}) = \frac{V_{\text{in}}}{(10\text{V})(R3 + R13)C3}$$

For best performance, R3 and R13 should be chosen to provide 1 mA of drive current at the full-scale voltage produced at pin 3 of the AD654 (U3). The input stage of the AD654 is an op-amp; thus, it will work to make the voltage at pin 3 of U3 equal to the voltage seen at pin 4 of U3 (pins 3 and 4 are the input terminals of the op amp). Since the amplified sensor output will be 4.5 V at full-scale pressure,  $R3 + R13$  should be approximately equal to 4.5 k $\Omega$  to have optimal linearity performance. Once the total resistance from pin 3 of U3 to ground is set, the value of C3 will determine the full-scale frequency output of the V/F. Trimpot R13 should be sized (relative to R3 value) to provide the desired amount of full-scale frequency adjustment. The zero-pressure frequency is adjusted via the offset adjust provided for calibrating the offset voltage of the signal conditioned sensor output. For additional information on using this particular V/F converter, see the applications information provided in the Analog Devices Data Conversion Products Databook.

The frequency output has its edge transitions "sped" up by a small-signal FET inverter. This final output is directly compatible with microprocessor timer inputs, as well as any

other high-speed CMOS logic. The amplifier portion of this circuit has been patented by Motorola Inc. and was introduced on evaluation board DEVB150A. Additional information pertaining to this circuit and the evaluation board DEVB150A is contained in Motorola Application Note AN1313.<sup>1</sup>

### TEST/CALIBRATION PROCEDURE

1. Connect a +12 V supply between B+ and GND terminals on the connector CN1.
2. Connect a frequency counter or scope probe on the  $F_{\text{out}}$  terminal of CN1 or on TP1 with the test instrumentation ground clipped to TP3 or GND.
3. Turn the power switch, S1, to the on position. Power LED, D1, should be illuminated. Verify that the voltage at TP2 and TP4 (relative to GND or TP3) is 5 V and 8 V, respectively. While monitoring the frequency output by whichever means one has chosen, one should see a 50% duty cycle square wave signal.
4. Turn the wiper of the OFFSET adjust trimpot, R12, to the approximate center of the pot.
5. Apply 100 kPa to pressure port P1 of the MPX2100DP (topside port on marked side of the package) sensor, X1.
6. Adjust the FULL-SCALE trimpot, R13, until the output frequency is 10 kHz. If 10 kHz is not within the trim range of the full-scale adjustment trimpot, tweak the offset adjust trimpot to obtain 10 kHz (remember, the offset pot was at an arbitrary midrange setting as per step 4).
7. Apply zero pressure to the pressure port (i.e., both ports at ambient pressure, no differential pressure applied). Adjust OFFSET trimpot so frequency output is 1 kHz.
8. Verify that zero pressure and full-scale pressure (100 kPa) produce 1 and 10 kHz respectively, at  $F_{\text{out}}$  and/or TP1. A second iteration of adjustment on both full-scale and offset may be necessary to fine tune the 1 – 10 kHz range.

### CONCLUSION

Transforming conventional analog voltage sensor outputs to frequency has great utility for a variety of applications. Sensing remotely and/or in noisy environments is particularly challenging for low-level (mV) voltage output sensors such as the MPX2000 Series pressure sensors. Converting the MPX2000 sensor output to frequency is relatively easy to accomplish, while providing the noise immunity required for accurate pressure sensing. The evaluation board presented is an excellent tool for either "stand-alone" evaluation of the MPX2000 Series pressure sensors or as a building block for system prototyping which can make use of DEVB160 as a "drop-in" frequency output sensor solution. The output of the DEVB160 circuit is ideally conditioned for interfacing to MCU timer inputs that can measure the sensor frequency signal.


### REFERENCES

1. Schultz, Warren (Motorola, Inc.), "Sensor Building Block Evaluation Board," Motorola Application Note AN1313.

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